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# Translation

## HIGH-POWER LASERS AND THEIR APPLICATION

By

V.S. Letokhov and N.D. Ustinov

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HIGH-POWER LASERS AND THEIR APPLICATION

Moscow MOSHCHNYYE LAZERY I IKH PRIMENENIYE 1980 pp 1-112

[Article by V. S. Letokhov, N. D. Ustinov]

[Text] A discussion is presented of the modern state of the art with respect to high-power lasers, and the basic areas of their application are illustrated: high-temperature heating of matter, laser separation of isotopes and obtaining pure materials, laser jet thrust, lunar location, and so on.

The book is designed for a broad class of readers interested in the application of high-power lasers in various areas of science and engineering.

# 1. INTRODUCTION

## 1.1. Energy Density of Various Isotopes

One of the primary trends in the development of modern applied physics and engineering is obtaining higher and higher energy densities, that is, the energy per unit volume and also finding means of releasing it in shorter and shorter times. Rapid progress in quantum electronics created and developed to a significant degree by the labors of prominent Soviet scientists academicians N. G. Basov and A. M. Prokhorov and their scientific schools, has led to the creation of a large family of high-power lasers. The high-power lasers have theoretically opened up new possibility both for obtaining record-high energy concentrations in time and space and extraordinarily convenient feeding of light energy to matter. This is clear from Table 1 in which a comparison is made between the energy and power of different energy sources used to create high energy densities.

We call the entire system of accumulation, transmission and conversion of energy in space and time the "energy source." This can be a capacitor bank which discharges the stored electric power in microseconds, chemical or nuclear explosive in which the energy is "stored" at the plant and released as a result of fast chemical or chain nuclear reaction; high-current fast-electron beam accelerated and concentrated in a small volume by electromagnetic fields and, of course, a powerful photon beam emitted by the laser consuming electrical, chemical, thermal or any other type of energy. Table 1 shows the values of the density of all of these energy sources and also the power densities reached for fast release of the stored energy in the electric discharge, for ordinary or nuclear blast and also when focusing a high-current, fast-electron or photon beam of a high-power laser on a target.

A powerful electric discharge and chemical explosive have approximately identical energy and power densities. In a nuclear explosion exceptionally high energy and power densities are achieved which exceed the parameters of a powerful electric discharge and the ordinary explosion by approximately a million times. However, in all these sources energy transportation has required: electric power over wires or mechanical transportation of chemical energy. In an electron beam a more convenient transportation charged particle is achieved, but there are restrictions on the energy density as a result of their repulsion among each other. A photon beam is free of

these deficiencies. When focusing powerful laser emission, energy and power densities are achieved which are equal to or even exceed the densities of a nuclear blast. The high light energy densities of a laser are achieved as a result of the energy concentration in a very small volume (in practice $10^{-6}$ to $10^{-7}$ $cm^3$), and high power densities, as a the result of concentration and release of energy in a very small time interval (from $10^{-8}$ to $10^{-11}$ sec) with relatively low total energy ($10^3$ to $10^4$ joules) by comparison with the total energy of an ordinary ($10^6$ to $10^8$ joules) or by the nuclear ($10^{13}$ to $10^{15}$ joules) blast. The flexibility of the feeding and the concentration of a coherent radiation light guide on a target, the possibility of laboratory experiments with exceptionally high energy and power densities previously attainable only in nuclear blasts place high-energy pulsed lasers out of the competition among all of the known "superfast" energy sources.

Table 1. Energy sources used to obtain high energy densities

| Energy source | Energy density joules/$cm^3$ | Power density watts/$cm^3$ |
|---|---|---|
| Electrical capacitor | $10^{-2}$ | -- |
| Electric discharge | $10^{-4}$ | $10^8$-$10^9$ |
| Chemical explosive | $10^4$ | $10^9$ |
| High-current electron beam | $10^6$ | $10^{13}$-$10^{14}$ |
| Nuclear explosive | $10^{10}$-$10^{11}$ | $10^{16}$-$10^{18}$ |
| Powerful focused laser beam | $10^{10}$-$10^{12}$ | $10^{20}$-$10^{22}$ |
| Annihilation of matter ($\rho$ = 10 $g/cm^3$) | $10^{15}$ | -- |

The energy density attained at the present time on the most powerful lasers is a total of a thousand times less than the energy density contained in matter with a density of $\rho$ = 10 to 20 $g/cm^3$, which can be released in the case of complete conversion of mass to energy in the annihilation process ($\varepsilon = \rho c^2$, where $\rho$ is the density of the matter; $c = 3 \cdot 10^{10}$ cm/sec is the speed of light). It is possible to count on achieving such a record (but not maximum!) value as progress is made in the techniques and equipment for obtaining powerful laser pulses, at the beginning of which we find ourselves at this time.

1.2. Coherent Radiation

Lasers are essentially converters of relatively low quality energy (thermal, chemical, electrical, and so on) to coherent radiation energy which is a higher quality form of energy. Using the terminology adopted in thermodynamics, it is possible to state that the laser is a device which decreases entropy as a result of loss of some portion of the energy. This can be especially clearly seen in the example of a laser with optical excitation (or, as is stated in quantum electronics, a laser with optical pumping),

for example, the first ruby laser. A simplified diagram of it appears in Figure 1. Electric pulse discharge in a flash tube is a bright optical emission pulse with an energy on the order of a kilojoule and a duration of several milliseconds, that is, the light flash has a power of several hundreds of kilowatts. However, the spectrum of this light flash occupies the entire visible range and is close to the spectrum of thermodynamically equilibrium radiation (or the black body radiation) with a temperature of 4000 to 7000°. The radiation of this flash is nondirectional and is gathered by a reflecting ruby crystal illumination system, which is the "core" of the laser. Part of the light energy of the flash is absorbed by chromium ions contained in a corundum crystal, and it is stored in the form of the energy of the excitations of these ions in the metastable state.

There are approximately $2 \cdot 10^{19}$ chromium ions per cubic centimeter, and the energy of excitation of an ion to the metastable state is $2.8 \cdot 10^{-19}$ joules. Therefore on excitation of half of all the ions to this state, the density of the stored energy is 2.8 joules/$cm^3$.

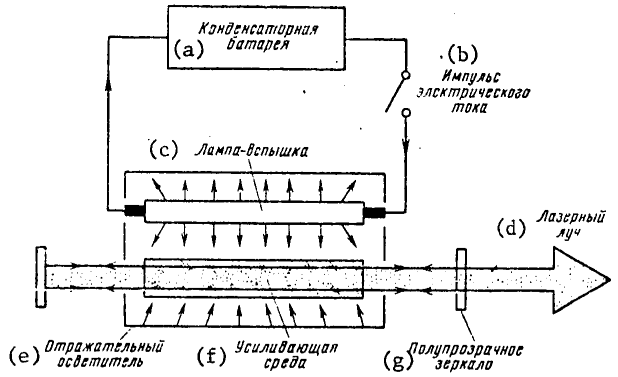


Figure 1. Simplified diagram of a laser with optical pumping by flash tube emission.

Key:
a. capacitor bank
b. electric current pulse
c. flash tube
d. laser beam
e. reflecting enumerator
f. amplifying medium
g. semitransparent mirror

When the number of excited chromium ions in the metastable state exceeds the number of chromium ions in the ground state, that is, the so-called population inversion of two quantum levels is created, the chromium ions, instead of absorption, began to amplify the radiation propagated between the resonator mirrors. As a result of the avalanche-like build-up of the radiation intensity, the energy stored in the crystal is emitted in the form of a directional light beam. In the simplest case where we do not specially control the process of amplification and generation of the light, the ruby laser emits a pulse with an energy of about 1 joule in 1 millisecond, that

is, with a total power of about 1 kilowatt. The power of the laser pulse is a thousand times less than the power of the flash tube feeding the laser. However, in contrast to the radiation of the flash tube, the laser emission is highly directional and, consequently, can be focused on a small area, at the limit with a dimension of about the laser radiation wavelength $\lambda_{las}$ = 0.69 microns. The radiation intensity at the focal point can, consequently, reach values of 1 kilowatt/$\lambda^2_{las} \approx 10^{11}$ watts/cm$^2$. This value is millions of times higher than the radiation intensity from the surface of the flash tube.

Thus, the first most important property of laser emission consists in its directionalness which is connected with the so-called spatial coherence. Spatial coherence means that the light can be propagated in the form of an almost plane wave, the divergence of which does not exceed by too much the so-called minimum divergence as a result of the light wave diffraction:

$$\phi_{dif} \approx \lambda_{las}/a, \qquad (1.1)$$

where a is the laser beam diameter. This spatially coherent wave can be focused by means of an optical system made up of mirrors or lenses on an area with a dimension of about the light wave length of $\lambda_{las}$. The capacity to be focused on a small spot is the most important property of a spatially coherent light beam.

The laser also converts the spectral composition of the flash tube emission. The pumping radiation has a solid spectrum, and the laser radiation is highly monochromatic, inasmuch as on the basis of the operating principle the laser generates coherent light oscillations on the frequency of maximum amplification and maximum light losses in the resonator. For example, the flash tube has a solid spectrum with a width of several thousands of angstroms, and the ruby laser emission can be concentrated in a very narrow spectral interval with a width of about 0.001 Å. Therefore an enormous increase in spectral brightness of the radiation is achieved using the laser.

In the example of a ruby laser with optical pumping it is clear how the laser converts the low-quality energy to coherent light, that is, to the maximum high-quality form of energy. In the language of thermodynamics this means that the incoherent radiation of the flash tube with comparatively low temperature and high entropy is converted to coherent radiation with exceptionally high equivalent temperature and extremely low entropy. Of course, this is also true for lasers with other, nonoptical pumping sources, although the proof of this statement is less obvious for them.

The high power of the laser radiation, the spatial coherence and monochromatic nature, the possibility of shaping short coherent light pulses and tuning the radiation frequency permits exceptionally flexible operation with coherent light, the application of it for the most varied purposes. In essence, with the birth of quantum electronics we for the first time were

able by choice to convert and concentrate light energy in space, time and spectrum to the degree it was possible to do this, for example, with electromagnetic energy in the lower frequency range (from direct current to superhigh frequency).

The creation of lasers led to the discovery of a new field of science and engineering which solves the problems of obtaining, controlling and using light energy. Obviously, the present period of the assimilation of electromagnetic oscillations in the optical range logically follows the old period of the discovery and assimilation of electric power. Now it is difficult to predict all of the consequences of the assimilation of this field, but a number of highly prospective areas connected with the application of powerful laser emission have already been investigated quite clearly. Therefore we consider it useful to tell the readers not familiar with this field of science and engineering about the modern achievements in the field of creating powerful lasers of various types, the problems encountered on the path of their development, and the applications of powerful laser emission.

1.3. Types of Powerful Lasers

There are two types of powerful lasers: pulse, emitting light in the form of one flash or a series of flashes and continuous, emitting light for a long period of time. The first laser in the world, which was created in 1960 by T. Mayman (the Hughes Company, United States) was a pulse laser. It operated on a ruby crystal and emitted a light pulse with the power of approximately one kilowatt and a duration of about 1 millisecond. Today powerful multistage and multichannel neodymium glass lasers have been build which are capable of generating a coherent light pulse with an energy to $10^4$ joules for a time of about 1 nanosecond, that is, pulses with a power of $10^{13}$ watts = 10 Twatts. Thus, in the last 17 years it was possible to increase the coherent light pulse power by $10^{10}$ times. This rapid growth of power was achieved as a result of the invention and realization of various types and operating modes of lasers. The control of the generation process which consists in fast emission of the energy accumulated in the core in the form of a very short pulse lasting about 10 nanoseconds (the Q-factor modulation mode or Q-modulation) made it possible to increase the pulse power to $10^8$ watts. Amplification of the pulse in the multistage amplifier gave an increase in energy approximately to a level of 100 joules and power to $10^{11}$ to $10^{12}$ watts. Finally, the application of large-diameter laser disc amplifiers (to 30 cm) and parallel stages of amplifiers with subsequent energy summation on the target offered the possibility of generating pulses with an energy of 1 to 10 kilojoules and a power of $10^{12}$ to $10^{13}$ watts.

Figure 2, a shows the increase in power of coherent light pulses by years as laser engineering has developed. Progress was made exclusively as a result of the development of methods of controlling the process of laser generation (reduction of the pulse generation) and amplification of the pulses in the multistage and multichannel devices (an increase in the pulse energy). The increase in energy stored and emitted in the form of coherent light by a unit volume of the core was comparatively small, and therefore in powerful

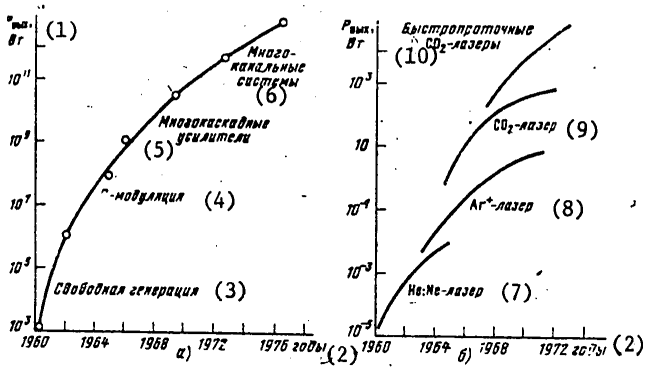


Figure 2. Growth of the output power of the pulse (a) and continuous (b) lasers by years.

Key:
1. $P_{out}$
2. years
3. free generation
4. Q-modulation
5. multistage amplifiers
6. multichannel systems
7. He:Ne-laser
8. $Ag^+$-laser
9. $Co_2$-laser
10. fast-flow $CO_2$ lasers

lasers, large core volumes are used by necessity (thousands and more cubic decimeters). When building powerful lasers, such problems arise as nonlinear distortion of powerful light pulses in the core which changes their parameters in the strong light field of the transmitted light pulse, self-damage of the core and the operating elements of the laser in the powerful light field, and so on. As a result, a new area of applied optics has appeared -- "power" optics of elements resistant to powerful radiation. All of these problems of high-power monopulse lasers will be discussed briefly in Chapter 2.

The first continuous laser was built by A. Javan in 1960 (Bell Telephone Company, United States) soon after the creation of the first ruby laser. It used glow discharge in an Ag:Ne-gas mixture, and its output power was fractions of a milliwatt. Today powerful continuous carbon dioxide lasers have been built with a power (according to published data) on the order of 100 kilowatts. In the last 17 years the continuous laser power has increased by approximately $10^{10}$ times. This was achieved as a result of the discovery of new active laser media, methods of pumping them and the operating modes of continuous lasers. On making the transition from glow discharge in the low-pressure He:Ne-laser to high-current discharge in argon, a generation power of about 10 watts was obtained (in recent years, more than 100 watts) in the visible band on the argon ion transitions. The next step was the discovery of the laser effect on the vibrational transitions of the $CO_2$ molecule in discharge of a mixture of $CO_2$:$N_2$:He, that is, the transition to

generation on the lower vibrational levels of the molecules. Thus, the power was increased to several hundreds of watts. Finally, the solution of the problem of heat release from the pumping region by continuous blowing of the gas mixture combined with using the high-power pumping source (electric discharge, heating and gas dynamic expansion) permitted the power to be increased to 100 kilowatts, and this, obviously, is not the limit. Figure 2,b shows the growth of the output power of continuous lasers of different types by years. In contrast to the powerful monopulse lasers, the increase in power was caused almost completely by the discovery of new types of laser media and methods of stimulating them. The problems of powerful continuous lasers will be investigated in Chapter 3.

The so-called pulse-periodic lasers which generate powerful pulses of short duration with quite repetition frequency (from tens of hertz to tens of kilohertz) occupy an intermediate position between the powerful monopulse lasers and powerful continuous lasers. On the one hand, the pulse-periodic lasers must insure quite high peak power, and on the other hand, the average output power of them is quite high, and therefore on creation of them the same difficulties arise as when creating continuous lasers. A standard example of such laser is the aluminum-yttrium garnet crystal laser with an admixture of neodymium ions (YAG:$Nd3^{+}$) capable of generating pulses with a power of hundreds of megawatts and duration of tens of nanoseconds with repetition frequency of several tens of hertz having an average power of tens of watts. Still higher average powers on the order of a kilowatt or more are reached in the pulse-periodic electric discharge laser based on a mixture of $CO_2$:$N_2$:He. In the last few years, it has become possible significantly to increase the average power of the pulse-periodic lasers based on dyes with pumping by powerful flash tubes. With an average power level of 100 watts the wavelength of the dye lasers can be tuned in the visible band, which has opened up theoretically new applications. The entire group of these problems will be investigated in Chapter 4.

1.5. Areas of Application of High-Power Lasers

The progress in the development of the ideas and the development of powerful lasers is directly connected with extraordinarily broad possibilities of their applications, beginning with prospective basic research and ending with specific technological applications in production.

The electric field intensity at the focal point of a powerful laser pulse approaches the intensity of the intraatomic fields. Therefore the behavior of even transparent optical media, for example, glass, in a powerful light field will become essentially nonlinear, for the index of refraction and the absorption coefficient change under the effect of the transmitted powerful pulse. Special crystals called nonlinear change their characteristics even in unfocused light beams of moderate power. At the present time a new area of research has arisen -- nonlinear optics -- in which Soviet scientists and, above all, the works of the scientific schools of academician R. V. Khokhlov have obtained basic results. In Chapter 5 we shall briefly consider the application of high-power lasers in the investigation of nonlinear optical

phenomena. The formation and the propagation of powerful laser beams is connected in the closest way with the nonlinear properties of the atmosphere and optical media which will to a significant degree hold up the progress of powerful lasers. Therefore at the end of Chapter 9 we shall return to this problem.

If laser emission with an energy density, for example, of $10^{10}$ joules/cm$^3$ is converted to thermal energy (with the same density) of the condensed medium, then a temperature of hundreds of millions of degrees will be achieved, that is, the temperature for which thermonuclear reactions occur. This is the basis for the application of powerful laser pulses for realization of controlled thermonuclear fusion. Finally, even for more moderate temperatures of several millions of degrees, experimental radiation becomes available in the laboratory under reproducible conditions of high-temperature phenomena which up to now could be investigated only in the presence of nuclear explosions. In a high-temperature plasma created by a powerful light pulse, thermodynamically unequilibrium conditions occur for a short period of time under which inversion of the population of the quantum levels of highly ionized atoms is possible along with the occurrence of a laser effect in the soft x-ray band (10-100 Å). Both of these basic applications of laser radiation are discussed in Chapter 6.

Coherent radiation can be theoretically obtained from any wavelength -- from vacuum ultraviolet to the submillimeter range. Although this entire spectral interval has not been completely assimilated by sufficiently powerful lasers, on many wavelengths already today frequently-tunable intense coherent light is attainable. Using tunable lasers, the possibility has been demonstrated of selective laser radiation effects on atoms and molecules of a defined variety, in particular, a given isotopic composition. This new prospective area of application of coherent light has begun to be developed comparatively recently, after laser engineering reached a higher level required for the control of the laser emission wavelength. In Chapter 7 we shall investigate the basic problems of the selective effect of laser emission on matter.

The most stable material is evaporated and heated at the focal point of a powerful laser pulse, and the focused powerful continuous laser emission is capable of heating, melting and evaporating refractory materials to great depth and with high speed. The creation of comparatively simple and effective powerful molecular lasers has made it possible to apply laser radiation for welding and cutting of large parts and tempering of alloys. This potentially expanding area of industrial application is still in the initial state of development, but has very large prospects. At the present time the laser treatment of materials is being used at the enterprises of the electronics industry, in precision machine building and even in the automobile industry. It will be fully realized as simple, reliable laser engineering is developed. Chapter 8 discusses the applications of laser emission based on the thermal effect. In addition to using lasers when treating materials, we shall also investigate the interesting possibility of creating a laser jet engine.

A collimated light beam with diffraction divergence even at far cosmic distances insures an illumination level sufficient for the reception of an echo on the earth. Successful and systematic experiments with respect to laser location of the moon have been based on this, and not only communications but also energy transmission at cosmic distances are prospective. The development of the techniques and equipment for powerful lasers and their applications has placed a number of problems before applied optics which it had not encountered before. In an intense light field optically uniform, transparent media for ordinary light change their optical properties, for example, they began to focus or defocus the laser beam, anomalously to absorb its energy, and so on. Therefore entirely new problems of creating the elements of so-called "power optics" stable in powerful fields, the formation of light beams which are subject the least to nonlinear distortions and in the final analysis the development of methods of illumination and compensation of nonlinear distortions on transmission of powerful laser pulses in optical media and the atmosphere, have arisen. The last area based on self-correction or adaptation of the optical system to the possible changes in its properties in a powerful laser field represents a new step in the development of optical systems. This area of modern optics born primarily from the requirements of powerful lasers is now called adaptive optics. All of these problems have been briefly touched on in different chapters.

In this brochure we shall try to give the readers an outline of the modern state of the art of the problem of powerful lasers, their applications and problems connected with this. Accenting the attention on new, prospective areas and approaches which can turn out to be useful to the specialists on adjacent fields, we, of course, do not have the possibility of detailed investigation of each problem. The interested reader can always refer to specialized handbooks and survey articles to which we give basic references. As for the readers who require references to original papers and additional information or to whom suggestions occur when reading our booklet, we request that they write us at our address.

## 2. POWERFUL PULSE LASERS

### 2.1. Principles of Obtaining Powerful Light Pulses

Figure 1 shows a simplified diagram of a pulse laser with flash tube pumping. This type of laser emits a coherent light pulse as a result of the pulse nature of the excitation. The operating mode of the laser not controlled by any additional elements, with the exception of the pumping source, is called the free generation mode. In this mode the laser emits a light pulse with a power even less than the radiation power of the flash tube that pumps the laser inasmuch as the generation time is approximately equal to the pumping time, and the efficiency of the laser does not exceed tenths of a percentage, and consequently, the energy of the laser flash is hundreds of times less than the energy of emission of the flash tube.

A much higher generation power is achieved in the so-called Q-factor modulation mode which is based on using the effect of storing the energy of excitation on the metastable levels of the ions in the core with subsequent emission of the stored energy in the form of a very short generation pulse with a duration of tens of nanoseconds, that is, $10^4$ to $10^5$ times shorter than the pumping time in the millisecond band. Here, a high-speed optical shutter is placed in the laser resonator which uses the Kerr effect, the Pockels effect or other effects. The shutter is closed during the period of pumping the core, and it does not permit multiple reflections of light between the resonator mirrors, that is, it does not permit the occurrence of generation. This makes it possible to store a sufficiently large number of excited particles. With fast opening of the shutter the laser turns out to be in a strongly overexcited state inasmuch as the amplification of the core greatly exceeds the light losses in the resonator with the open shutter. As a result, the intensity of the radiation builds up in avalanche fashion in a short time, and the greater part of the energy stored in the core is luminesced in a total of few passes by the resonator light. The light passes through a resonator of length of $L = 30$ cm in a time $T = L/c = 4$ nanoseconds, and therefore the standard powerful pulse duration of a laser with modulated Q-factor will be $\tau_p$ = 10-20 nanoseconds. With a radiation pulse power totalling one joule, a peak power of 50-100 megawatts is achieved. A further increase in power by increasing the energy of the generated pulse turns out to have low efficiency as a result of the difficulty of controlling the

short pulse generation mode of the laser with high energy, destruction of the controlling elements inside the resonator by the powerful laser emission, and so on.

Another operating mode of the multimode laser is found -- the mode synchronization or capture regime -- which permits generation of much shorter pulses with a duration of several picoseconds and much less time for the light to pass through the laser resonator. The lasers with a wide amplification line, for example, neodymium glass lasers, operate simultaneously on many axial modes, the frequency interval between which will be $\Delta\nu = c/2L$. The phases of the light oscillations of the axial modes are not connected to each other, and therefore the multimode emission resembles light noise as a result of interference of the light oscillations on different frequencies. The individual fluctuation flashes of intensity have a duration of $\tau_{fl} \approx T/N$, where $T = 2L/c$; N is the number of interfering axial modes. Usually $N \approx 10^2$ to $10^3$; therefore the duration of the intensity fluctuations lies in the picosecond range. By varying the number of synchronized modes it is possible to regulate their duration within the interval from unit to hundreds of picoseconds. Placing the illuminating nonlinear absorber inside the resonator, it is possible to realize the mode of predominant amplification of the fluctuation surges of intensity of ultrashort length. This is possible inasmuch as the more powerful intensity fluctuations more strongly illuminate the nonlinear absorber and, consequently, are amplified with multiple transmissions much more rapidly than the remaining less intense radiation. In the final analysis, one pulse of ultrashort duration is formed which luminesces the energy stored in the amplifying medium. With each reflection from the semitransparent output mirror, part of the pulse leaves the resonator; therefore the output emission of the laser in the mode self-synchronization regime is a train of 20-50 picosecond pulses with a time interval $T = 2L/c$ lying in the nanosecond range. By using a fast optoelectronic shutter it is possible to isolate a single ultrashort pulse from this train.

Of course, the energy of one ultrashort pulse will be a total of several millijoules. For further increase in pulse energy of nanosecond or picosecond duration it is amplified in a series of laser amplifiers called a multistage amplifier. In the core of the amplifier, just as the laser, energy is stored as a result of pumping, the magnitude of which is proportional to the total volume of the core. The main problem here is prevention of self-excitation of the amplifier with a high amplification coefficient $K = 10^3$ to $10^5$ which is attained automatically with large dimensions of the amplifier. Therefore the series or chain of amplifiers optically insulated from each other until the arrival of the amplified pulse from the master oscillator, is used. There is a limiting intensity which the optical medium is capable of transmitting without noticeable distortion of the laser beam. Therefore in order to increase the output power and the laser pulse power, it is necessary to increase the area of the transverse cross section of the amplifying stages as the amplification increases. Thus, as a result of the large diameter of the terminal amplifying stages (10-30 cm) it is possible to increase the pulse power to 100-1000 joules while maintaining high intensity of emission. However, a further increase in energy in one laser beam is

in practice impossible, for it is impossible to increase the diameter of the amplifier to several tens of centimeters as a result of the occurrence of spurious self-excitation in the transmitted direction. Therefore for further increase in energy, amplification of the pulse in several (10-100) parallel amplifying stages with subsequent summation of the pulse energy on one target is used. In the multichannel amplifier it is possible to increase the energy to 10 kilojoules and it is possible to achieve an increase in it to 100 kilojoules.

The pulse generation modes of the laser (Q-factor modulation and mode self-synchronization) and the pulse amplification modes (multistage and multichannel) were discovered and discussed in detail in 1962-1970 in the USSR and the United States. The center of this work in the USSR is the Physics Institute imeni P. N. Lebedev of the USSR Academy of Sciences where the basic results were obtained. In recent years a large volume of studies, especially the techniques and equipment of multistage and multichannel amplification of large-diameter light beams (10-30 cm) have been performed in the United States at the Lawrence Livermore Laboratory.

The principles of constructing the powerful lasers to obtain short pulses with high energy are quite universal and are used for any type of core. Of course, in real units, many more special elements are used to retain high quality of the laser beam, prevent amplification of spontaneous emission, the formation of pulses of defined shape, and so on. Let us consider them briefly in the example of powerful pulse devices using neodymium glass as the core. We immediately note that all of these devices are created for experiments in laser controlled thermonuclear fusion.

2.2. Powerful Neodymium Glass Devices

In these devices the active particles are neodymium ions included in the glass matrix with a concentration of several percentages. The inversion of the level populations and the laser effect occur at the forbidden transition from the metastable state to the state close to the ground state and strongly connected with it as a result of the interaction with phonons (Figure 3,a). The amplification and generation wavelength is 1.06 microns. The excitation of the neodymium ions and their storage in the excited state are realized by optical pumping by a powerful flash tube. From the continuous pumping radiation spectrum the neodymium ions absorb photons with a wavelength of 5000 to 9000 Å. With powerful pumping it is possible to store energy of approximately 0.5 joules/$cm^3$. The population inversion and the amplification effect are maintained for 300 microseconds.

Figure 4 shows the schematics of the main elements of one channel of a multistage neodymium glass device which was designed to obtain pulses with an energy of 1000 joules and a duration in the subnanosecond range of 0.1 to 1.0 nanoseconds. The construction of this device is based on the above-discussed general principles. The master oscillator in the mode synchronization regime emits a train of subnanosecond pulses in which a single pulse is isolated. The initial pulse energy of the master oscillator is low (a

total of $10^{-3}$ joules), but it has well-controllable and reducible parameters. In the preliminary stages of the amplifier linear amplification of the pulse is realized. In this amplification mode, the pulse still is not capable of extraction of a noticeable part of the energy stored in the amplifying medium as a result of induced transitions. In the neodymium glass the nanosecond pulse stimulates emission of all of the metastable neodymium ions only when its energy flux reaches the values of the so-called saturation energy $\varepsilon_{sat}$ = = 6 joules/cm$^2$. Beginning with this value of the pulse energy through a unit transverse cross section the pulse gives up almost all of the energy stored in the active medium.

Unfortunately, in practice it is not possible to realize the operation of the terminal stages of the neodymium glass amplifiers in this continuous amplification mode for two reasons. With an energy flux of 1-2 joules/cm$^2$, damage occurs to the surfaces of the optical elements, and with a radiation intensity of 5 gigawatts/cm$^2$ (which corresponds to an energy flux of 5 joules/cm$^2$ for a pulse with a duration of one nanosecond and 0.5 joules/cm$^2$ for 0.1 nanosecond) self-focusing of the light beam occurs in the glass which leads to distortion of the wave front of the beam, loss of its energy and destruction of the glass itself. Therefore it is necessary to limit the laser radiation flux density, and in order to increase the pulse energy, as has already been noted, it is necessary to increase the transverse cross section of the amplifiers. With an aperture of 5-7 cm, glass rods are used as the amplifiers, but it is impossible to increase their diameter as a result of the difficulties of uniform excitation of them to great depth by the flash tube emission.

In order to increase the transverse dimensions of the active medium, glass plates are used instead of the rods. In particular, for large apertures, sets of glass discs are used with a thickness of several centimeters mounted at the Brewster angle and using pumping through the disc planes. The section of one of the disc amplifiers of the terminal stage is shown in Figure 4. In the preliminary amplification stages based on glass rods, the pulse energy reaches approximately 10 joules, and in each disc amplifier it increases by approximately 3-4 times. The maximum disc diameter is limited either by self excitation on the internal types of vibrations where the radiation begins to be amplified on propagation along the disc or by the losses of the stored energy to amplification of spontaneous fluorescent radiation of the excited ions called superluminescence. These effects can be suppressed significantly by using absorbing coatings along the edges of the discs, but in any case the maximum energy of the subnanosecond pulse, let us say, with a duration of 0.1 nanosecond in practice is limited to a value of 1-2 kilojoules. It is achieved in the chain of disc amplifiers with aperture of the last stage of 30 cm.

In reality, the schematic of a real multistage 1-10 Twatt amplifier is much more complicated, for it is necessary to deal with subsequent harmful phenomena unavoidably occurring in any multistaged amplifier: destruction of uniformity of intensity of the wave beam; self-excitation of stages of the amplifier as a result of their connection; destruction of the input stages

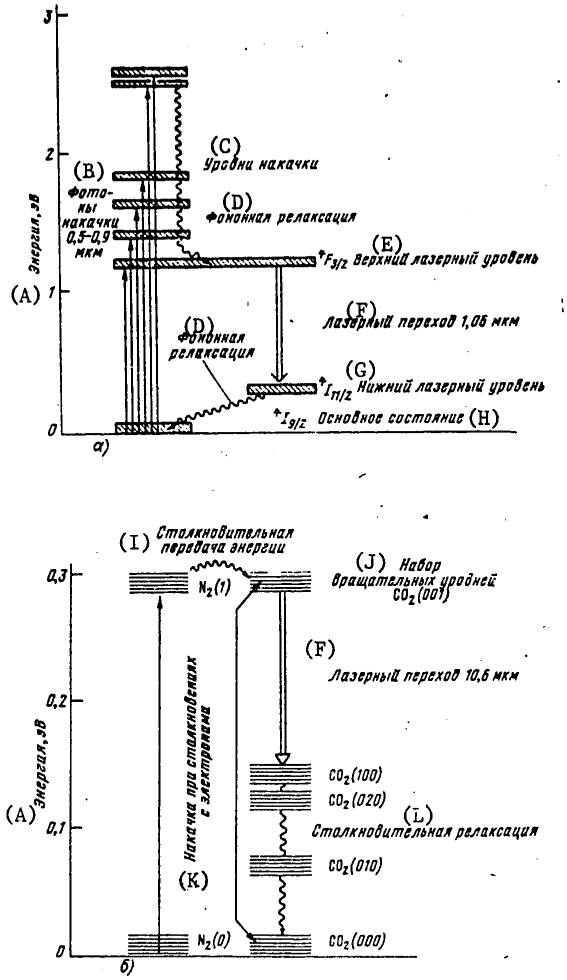


Figure 3. Diagram of the quantum levels and transitions participating in pumping and generation: a -- $Nd^{3+}$ ion in glass; b -- $CO_2$ molecules in a gas discharge mixture of $CO_2$:$N_2$:He.

Key:
A. energy, ev
B. pumping photons, 0.5-0.9 microns
C. pumping level
D. phonon relaxation
E. upper laser level
F. laser transition, ... microns
G. lower laser level
H. ground state
I. collision transmission of energy
J. set of rotational levels
K. pumping on collions with electrons
L. collision relaxation

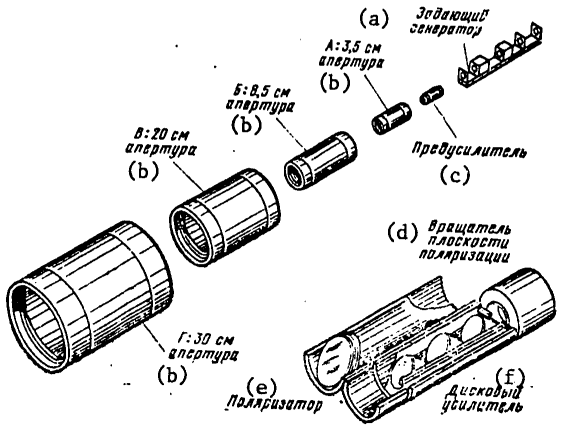


Figure 4. Chain of elements of a multistage neodymium glass amplifier with terminal disc amplifier (its section is given at the bottom) with 30 cm aperture.

Key: a. master oscillator
b. aperture
c. preamplifier
d. polarization plane rotator
e. disc amplifier
f. polarizer

of the device as a result of return of a large part of the energy from the target to the aperture of the terminal stage. In order to eliminate these phenomena an entire arsenal of receivers has been developed. Let us consider them briefly.

On transmission of a parallel light beam with uniform transverse intensity distribution through an opening of limited size, for example, through an amplifier or control element of finite diameter, diffraction of it takes place. As a result, at the exit instead of uniform intensity distribution, transverse intensity nonuniformities occur (interference rings or bands). On amplification the intensity at the peaks of the bands or the rings can reach the destruction threshold or the threshold of occurrence of self-focusing at the same time as the average intensity with respect to the beam aperture will be below this threshold. In order to obtain the maximum possible mean intensity with respect to the entire aperture it is necessary to achieve uniform intensity distribution with respect to cross section, excluding any interference bands and rings. Therefore in the powerful amplifiers it is undesirable to use ordinary irises with sharp discontinuous variation of the transmission to the edge. Instead of them, the so-called apodizing irises or "soft" apertures are used, the transmission of which decreases smoothly at the edges. Figure 5 shows the variation of the transverse intensity distribution with linear diffraction of a plane light wave on an ordinary iris with rectangular transmission characteristic and on an apodizing iris with smooth variation of the transmission. It is obvious that when

using an ordinary iris in transverse distribution, strong nonuniformities occur, and the application of a soft aperture essentially suppresses the nonuniformities of the intensity. In practice the apodizing irises are made using the application of an absorbing layer or other absorbers with variable thickness.

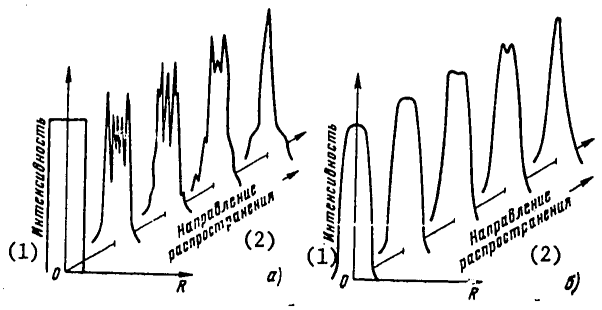


Figure 5. Deformation of a light beam with linear diffraction on the iris with sharp drop in transmission (a) and on an apodizing iris with smooth drop of transmission at the edges (b).

Key: 1. intensity
2. direction of propagation

Soviet scientist V. I. Bespalov and V. I. Talanov demonstrated that the process of development of self-focusing is significantly facilitated if there are intensity nonuniformities in the light beam in the transverse direction. In this case the light beam is self-focused not as a whole, but it is broken down into several beams formed from local intensity surges. This is the so-called "small scale self-focusing." Inasmuch as self-focusing limits the output power and pulse energy, special measures for suppressing the self-focusing are used in the powerful lasers. The self-focusing threshold of the entire beam depends strongly on the angle of divergence of the beam. On transmitting nonparallel beams but beams that diverge with an angle of several degrees through the amplifying stages, it is possible to raise the self-focusing threshold by many times.

However, this measure does not help to raise the fine-scale self-focusing threshold. Here it is necessary to decrease the nonuniformities of the spatial intensity distribution. For this purpose, along with the apodizing irises, spatial filters are used. Structurally the spatial filter is executed in the form of two cofocal lenses and an iris installed at the common focal point. The power of the laser pulse at the focal point is so great that breakdown of the air takes place. The plasma formed does not transmit the laser radiation. Therefore the entire spatial filter is placed in a vacuum chamber from which the air is pumped out. If the light beam has transverse small scale intensity nonuniformities, that is, it contains high

frequencies of the spatial spectrum, then on focusing the lead to the formation of spots with a size much greater than the minimum diffraction side $d_{dif} = c^{inp}_{dif} F_1$, where $F_1$ is the focal distance of the input ends of the filter. Selecting the hole diameter of the iris on the order of $d_{dif}$, it is possible to eliminate all of the high spatial frequencies from the light beam and obtain a light beam at the output of the spatial filter with diffraction divergence $\phi_{df}^{out} = (F_2/F_1)\phi^{inp}_{dif}$, where $F_2$ is the focal length of output lens. By selecting the focal lengths and diameters of the two lenses or objectives of the filter, it is possible simultaneously to match the diameter of the amplified light beam with increasing diameter of the output stages of the amplifier.

Another important function of the spatial filter installed between the amplifier stages consists in decreasing the optical coupling of them between each other and, consequently, the possibilities of their self-excitation. In the chain of amplifying stages the amplification coefficient reaches values of $10^5$ to $10^7$. Therefore even spontaneous emission of the core in a single pass of the chain can be amplified to such a degree that it begins to depopulate the excited levels of the active particles of the amplifying medium to the arrival of the amplified pulse. A narrow angular transmission iris of the spatial filter helps here. The amplified spontaneous emission occupies a wide angle close to the geometric angle of the amplifier $\phi_{geom} = d_{amp}/L_{amp}$, where $d_{amp}$ and $L_{amp}$ are the diameter and length of the amplifying stage which is much greater than the diffraction angle. The spatial filter transmits spontaneous radiation only in the diffraction angle, the intensity of which is below the admissible level, and therefore it has no significant influence on the parameters of the multistage amplifier.

As has already been noted, the density of the energy transmitted through the amplifying stages is in practice below the density of the saturation energy. This means that the amplification coefficient remains in practice unchanged after transmission of the pulse for a significant time (tens of microseconds). If during focusing of the radiation on the target, reflection from it occurs, then the light amplified in the opposite direction can reach the intensity causing damage to the core. Therefore it is necessary to "decouple," that is, optically isolate, the laser from the reflected radiation. The total optical decoupling of all of the stages of the amplifier and the protection of the amplifying stages from the return laser emission reflected from the target is achieved using a large number of optical insulators, the purpose of which consists in the transmission of laser radiation only for the short time of transmission of the amplified pulse and only in one direction -- from the input stage to the output and not back. For this purpose in the first amplifying stages having comparatively small diameter (to 2-3 cm) optoelectronic high-speed (time constant about 1 nanosecond) Kerr or Pockels cells are used. These cells are opened only for the time of transmission of the laser pulse, and at the time of arrival of the reflected light they close.

Another type of optical decoupling is the magnetooptical insulator based on the Faraday effect in certain varieties of glass placed in a longitudinal magnetic field. The field intensity is selected so that on transmission of light in the glass the polarization plane is rotated by 45°. On propagation of the light in the opposite direction, the polarization plane is rotated additionally by 45°, and the light is not transmitted by a polarizer installed at the insulator input. For the optical insulator of this type high speed is not required. The magnetic field can be created by a superconducting solenoid.

In order to increase the optical insulation of the stages and for absorption of weak background emission, illuminating cells are used which are in the form of an ordinary absorber (dye molecules in solution, glass colored by impurity ions), resonance-absorbing emission on the amplification wavelength ($\lambda$ = 1.06 microns). However, with sufficiently high intensity of the short pulse ($10^6$ to $10^9$ watts/cm$^2$) the absorber is illuminated as a result of excitation of all of the absorbing particles by the radiation itself. The illuminating nonlinear absorber is a very simple insulator of the stages for the low-intensity radiation. Usually it is used at the very beginning of amplification to increase the contrast of the emission pulse with respect to the unavoidable background by suppression of the random, weaker pulses with a background from the master oscillator.

After achievement of the maximum admissible energy flux and intensity in the amplifying stage further buildup of the energy takes place in the parallel amplifying stages through which the pulse is split from the terminal stage of the amplifier. The number of parallel channels depends on the required total energy and the limiting energy of one channel. The powerful multistage and multichannel neodymium glass amplifiers have been created and are being created at several of the laboratories in the USSR, the United States, France, Japan and other countries for performing experiments with respect to laser thermonuclear fusion. The most powerful devices were built in the United States and USSR. At the Physics Institute imeni P. N. Lebedev of the USSR Academy of Sciences in the Quantum Radio Physics Laboratory headed by academician N. G. Basov, the "Del'fin" [Dolphin] device was built on which it is expected that a pulse energy of 10 kilojoules will be obtained with a duration of 1 nanosecond on summation of the radiation of 216 parallel multistage amplification channels. Such a large number of channels is explained by the relatively small diameter (5 cm) of the terminal stages of the amplifier. After summation the pulse power will reach $10^{13}$ watts = 10 Twatts, and the radiation brightness, $10^{17}$ watts/cm$^2$-ster. Figure 6 shows an overall view of the room where the unique "Del'fin" device is installed. Its creation has become possible after the development and investigation of two prototypes -- the "Kal'mar" and "Flora." A record pulse energy for its time of 600 joules for 1 nanosecond was obtained on the "Kal'mar" device in 1970 with 9 parallel channels. On the 20-channel "Flora" device started up in 1975, a pulse energy of 1.5 kilojoules was obtained lasting 2 nanoseconds. The principles of multichannel amplification were worked out on these devices. In the preceding years (1963-1970) studies were made of the principles of linear and nonlinear multistage amplification of nanosecond and subnanosecond pulses to power levels of approximately 1 Twatt.

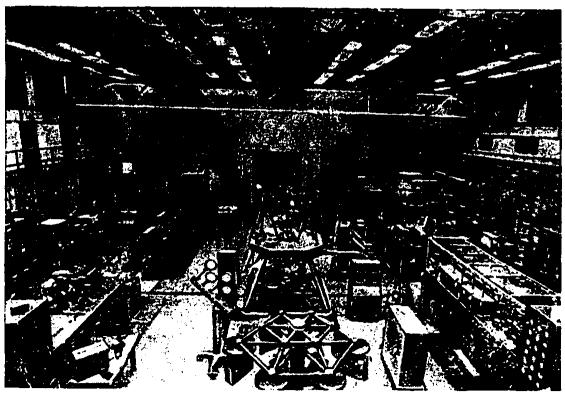

Figure 6. Outside view of the multichannel "Del'fin" neodymium glass unit created at the laboratory of academician N. G. Basov in the Physics Institute imeni P. N. Lebedev of the USSR Academy of Sciences.

At the Lawrence Livermore Laboratory (United States) which belongs to the US Power Research and Development Administration, the "Shiva" device was built. In this device the terminal state of the amplifier was constructed from neodymium glass discs with an aperture of the amplified beam of 30 cm. The output pulse power in one channel reaches approximately 1 kilojoule with a duration of 0.1 to 0.5 nanoseconds. In the upper part of Figure 7 we see a simplified diagram of a multistage amplifier which is one channel of the "Shiva" device. In this diagram the location of the above-described beam shapers, spatial filters and optical insulators is given. The length of this chain reaches 55 m and contains 11 amplification stages. In the lower part of Figure 7 we have a simplified diagram of the entire 12-channel device which occupies a special building. The output power of the device is 10 kjoules and with a pulse duration of 0.1-0.5 nanoseconds insures a pulse power from 100 to 20 Twatts, respectively. The cost of the device will be more than 20 million US dollars. The same figures shows the system for convergence of the radiation of the individual channels on a spherically irradiated target.

The powerful "Del'fin" and "Shiva" neodymium glass devices are at the present time the top of the engineering art in this field of quantum electronics.

However, the powerful neodymium glass lasers have very serious deficiencies forcing researchers to conduct a broad search for more prospective active means than neodymium glass. The basic deficiencies are the following: low efficiency (no more than 0.2%); low average power (approximately 1 pulse in 15 minutes for the powerful device); limitation of the pulse energy in one beam (channel). The low efficiency is a consequence of tube pumping, for

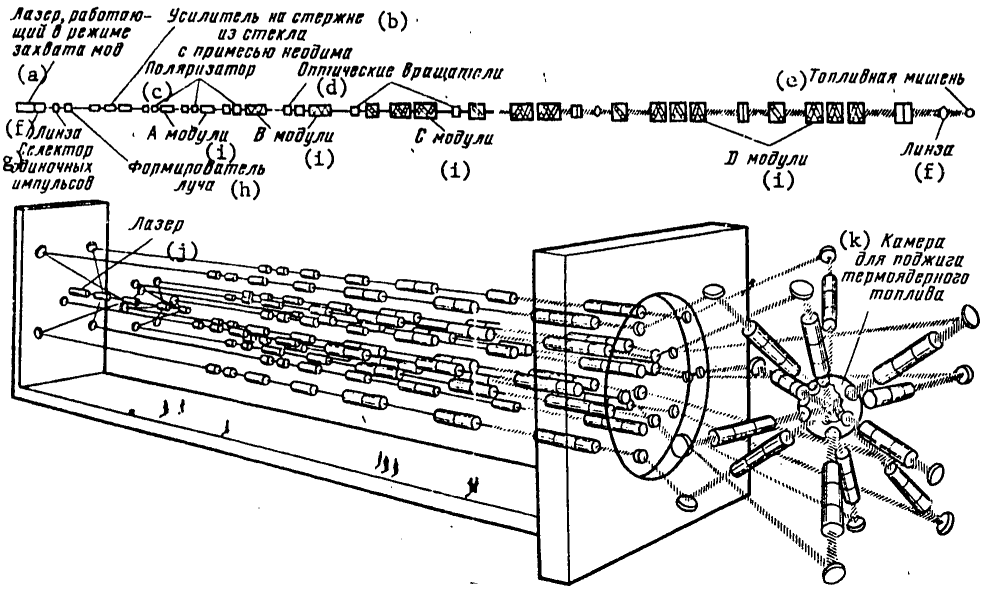


Figure 7. Simplified diagram of the 12-channel unique Shiva device (bottom) created at the Lawrence Livermore Laboratory. A simplified diagram of the multistage amplifier is presented at the top, that is, one channel of the device.

Key:
a. laser operating in the mode capture regime
b. glass rod amplifier with neodymium admixture
c. polarizer
d. optical rotators
e. fuel target
f. lens
g. single pulse selector
h. beam shaper
i. ... moduli
j. laser
k. thermonuclear fuel burning chamber

only a small part of the flash tube spectrum is absorbed by the neodymium ions in the glass and populates the upper laser level. The remaining energy heats up the glass, increasing the idle time during which the heated glass returns to the initial state. Hence, the low average power which is a consequence of the low thermal conductivity of the glass. To this it is necessary to add high cost of construction (approximately 100 US dollars per joule of nanosecond pulse energy). The maintenance is also very expeensive inasmuch as the glass deteriorates, and the pumping tubes has limited service life.

As an example of the exceptionally high requirements imposed on the conditions of manufacture and maintenance of the powerful unit it is possible to mention the requirements on air purity and purity of all of the optical surfaces on the path of the laser beams. A pumping pulse with an energy of 200 kilojoules and a peak power of 300 Mwatts (!) is fed to each terminal amplification stage based on glass discs. With such intense optical pumping any particles (thin film, dust particles, microinclusions, and so on) present on any surface evaporate, they explode and melt under the effect of the powerful flash tube radiation. All of this damages the optical surfaces of the large-diameter expensive amplifying stages. For these reasons the powerful neodymium glass units are considered only as an intermediate step in the development based on the accessibility and the developability of the neodymium glass technology. The powerful lasers of the next generation producing a power of 10 kilojoules or more will be constructed obviously on the basis of other active media. The first candidate is unconditionally the gas discharge in a mixture of $CO_2$:$N_2$:He gases. Let us discuss this problem.

## 2.3. High-Power Carbon Dioxide Lasers

The search for gas-discharge active media having higher efficiency than the He:Ne-laser led in 1964 to the discovery of the population inversion of the vibrational levels of the $CO_2$ molecule in the gas discharge plasma in a mixture of $CO_2$:$N_2$:He. The amplification on many rotational-vibrational transitions in the 10 micron range occurs as a result of very effective excitation of the oscillatory levels of the $N_2$ molecule by electrons with an energy of approximately 2 ev and resonance transition of this excitation to the $CO_2$ molecule on collision (Figure 3,b). The molecule collisions usually depopulate the lower vibrational level of the laser transition which also leads to the occurrence of an inversion. The high efficiency of this laser is determined by effective use of the electron energy. Here there is no long energy conversion chain (electric discharge → pumping radiation → excited neodymium ions) as occurs in neodymium glass. In contrast to the remaining gas lasers, the energy of the quanta generated by the $CO_2$ molecule is a total of half the excitation energy of the $N_2$ molecule. Therefore the efficiency of the $CO_2$-laser can reach 10-20%. The energy of the pulse $CO_2$-lasers generated by a unit volume did not exceed 1 millijoule/$cm^3$ until generation was achieved in 1970 in a $CO_2$:$N_2$:He-plasma of atmospheric, and then higher pressure.

For excitation of the gas mixture of atmospheric pressure, preionization by corona discharge is used, and for the energy pumping, use is made of an independent discharge, the duration of which is less than the transition time of the glow discharge to the arc discharge. This type of laser is simple and cheap. In order to improve the uniformity of the excitation of the discharge, other methods are used, for example, the photoionization of gas by ultraviolet radiation from dischargers distributed along the entire length of the transverse discharge. Such lasers are already being produced industrially in a number of countries and have found broad application.

In all of the vibrational-rotational transitions of the $CO_2$ molecule, energy of approximately 10 joules/liter is stored, and the inversion exists about 20 milliseconds. The strength of the active medium is determined by the breakdown threshold of the mixture generated by infrared radiation. The threshold flow of breakdown energy under a mixture pressure of 1 atmosphere is about 10 joules/$cm^2$. This is not the basic energy restriction, for the standard energy flux for which the infrared optical elements are damaged by radiation will be approximately 3 joules/$cm^2$. The pulse energy flux, under the effect of which luminescence of the energy stored in one of the vibrational-rotational transitions takes place is 0.01 joules/$cm^2$. The vibrational energy stored in the $CO_2$ molecule is distributed with respec to several tens of rotational levels. If the duration of the amplified pulse is much less than the time of the rotational relaxation, that is, the time of the transition of the $CO_2$ molecules between the different rotational levels in the presence of collisions, then it interacts only with one of the numerous vibrational-rotational transitions of the molecule. This creates difficulty in extraction of the energy stored in the terminal amplifiers, by the nanosecond monochromatic pulse. In order to eliminate this deficiency either the pulse of the master oscillator operating simultaneously on many vibrational-rotational lines is amplified or the pressure of the active medium is increased to several atmospheres. With an increase in pressure, the rotational relaxation time decreases proportionally, which greatly facilitates the extraction of the energy by a short pulse.

However, the creation of gas lasers with a mixture pressure of several atmospheres or higher is connected with serious difficulties. First, the uniform excitation by electric discharge of a large volume is very difficult to realize as a result of the occurrence of instability in the discharge which leads to the pinching of the discharge, transition of it to the arc regime. Secondly, with an increase in pressure as a result of buildup of the collision frequency of the excited molecules with neutral molecules and electrons, the role of the extinguishing collisions which deactivate the excited molecules increases. All of these difficulties were overcome successfully by academician N. G. Basov, et al at the Physics Institute of the USSR Academy of Sciences using pulse preionization of the dense gas mixture $CO_2$:$N_2$:He by a fast electron beam with an energy of about 1 Mev. Thus, it was possible to achieve uniform excitation of large volumes of gas pulse generation under the pressure of a gas mixture to 25 atmospheres. This electrical excitation regime with preionization is called independent discharge, and the laser itself, electroionization. This method of exciting the $CO_2$-amplifiers with a pressure of 3-5 atmospheres is used in the terminal stages of the high-power devices. With a pressure of the gas mixture of 3 atm, the energy flux of a pulse saturating the amplification of the active medium will be $\mathcal{E}_{sat}$ = = 0.04 joules/$cm^2$. The density of the stored energy increases to 30 joules/liter in all of the vibrational-rotational lines or to 2 joules/liter in one line. The time of existence of the inversion decreases to 7 microseconds, and the energy flux for which optical breakdown of the active medium takes place drops to 3 joules/$cm^2$. Figure 8 shows the transverse section of a high-pressure $CO_2$-laser amplifier with preionization of the discharge by a beam of fast electrons. Structurally, this amplifier is made up of two

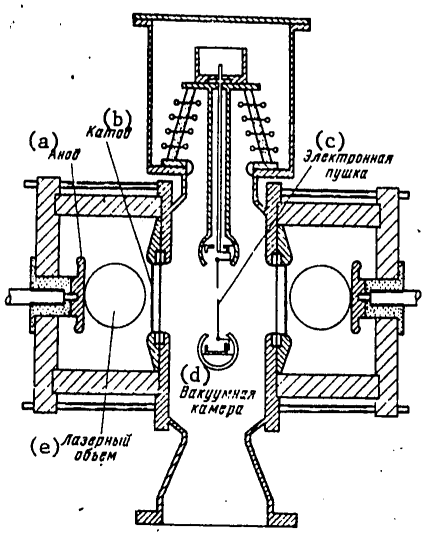


Figure 8. Section of the terminal amplifier based on a high-pressure $CO_2$:$N_2$:He gas mixture with preionization discharge by a beam of accelerated electrons. The amplifier has two symmetric laser (amplifying) volumes through which the laser pulse is passed.

Key: a. anode
b. cathode
c. electron gun
d. vacuum chamber
e. laser volume

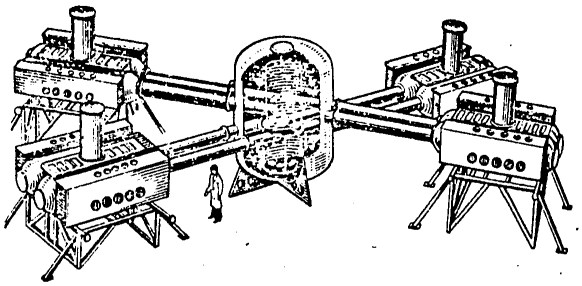

Figure 9. Overall view of the 8-channel carbon dioxide unit built at the Los Alamos research laboratory in the US (pulse energy 10 kilojoules, duration 1 nanosecond).

identical halves, and a radiation pulse from the preliminary stages is passed through each of them. The increase in pressure in the general amplifiers significantly increases the density of the stored energy and the energy pickup under the effect of a nanosecond pulse with an energy flux of $\mathcal{E} > \mathcal{E}_{sat}$.

The principles of constructing powerful carbon dioxide gas lasers which generate a short high-energy radiation pulse with wavelength of 10 microns are the same as for the above-described neodymium glass lasers. The carbon-dioxide devices are free of two basic deficiencies of the neodymium glass devices. First, the possibility of fast pumping of the heated gas after excitation insures much higher repetition frequency of the pulses which can theoretically reach several hundreds of pulses per second. Secondly, the efficiency of a laser when operating on several vibrational-rotational lines can reach 2-5% and possibly will be brought to 5-7%. The powerful carbon dioxide laser is much cheaper to build (approximately 100 US dollers per joule of output pulse energy) and to maintain. However, one deficiency remains both for the $CO_2$-devices and for the Nd-devices -- limited output power of the pulse reckoned for one aperture, that is, limitation of the energy of one channel of a multistage amplifier. It obviously lies within the range of 1-2 kilojoules for the nanosecond pulse. Therefore, just as in the case of neodymium glass, in order to obtain pulses with an energy of several kilojoules it is necessary to use amplification in any parallel channels. Figure 9 shows the general view of the 8-channel carbon dioxide unit built at the Los Alamos research laboratory in the United States for obtaining pulses with an energy of 10 kilojoules and lasting one nanosecond. The device was built for studies of laser controlled thermonuclear fusion. The construction of a still more powerful unit with 100 kilojoules nanosecond pulse energy has been started.

## 2.4. Prospective Pulse Laser Systems

None of the existing lasers completely satisfies the requirements imposed on a laser generating pulses of nanosecond duration with an energy of tens and hundreds of kilojoules with the pulse repetition frequency necessary for the applications, acceptable cost, required efficiency, and so on. It is possible that such an "ideal" laser will not be built. However, at the present time in many of the laboratories of certain countries a persistent search is being made for such a laser. Figure 10 shows the quantum system (atom, molecule, ion, and so on) of such an "ideal" laser, the search for which is being conducted by scientists.

The upper laser level must have be pumped easily and with high efficiency. This means that the ground quantum state must be connected with the upper pumping level by the transition permitted for optical or electron excitation with large cross section (that is, high probability) of excitation ($\sigma_{exc}$ = = $10^{-16}$ to $10^{-17}$ $cm^2$). The excited quantum system must make a transition rapidly and with low energy losses to a longer-lived state, which is the upper state of the laser transition. The lifetime of this state which determines the time of existence of the population inversion must be no less

than $10^{-6}$ sec. Otherwise it will be difficult to accumulate sufficiently high energy in the active medium. The lifetimes from hundreds of microseconds to several milliseconds or more are the most desirable. Of course, when accumulating particles there must be no transitions under the pumping effect or the interaction of excited particles from the metastable state to the higher levels. The density of the energy stored per unit volume of the active medium must be quite high in order that the dimensions of the laser be within reasonable limits.

The induced transition cross section $\sigma_{st}$ must be small, but entirely sufficient to extract the energy stored in the active medium under the effect of a pulse with an energy flux still not destroying the optical elements of the device. Consequently, the saturation of the amplification must be achieved for an energy flux of 1-10 joules/cm$^2$. The stimulated transition cross section $\sigma_{st}$ is proportional to $\mu^2/\Delta\omega$, where $\mu$ is the dipole moment of the transition of the quantum system between levels of the laser transition; $\Delta\omega$ is the amplification band width on this transition. Consequently, in order to obtain the required small size of cross section $\sigma_{st} = 10^{-20}$ cm$^2$ the dipole moment of the transition must be small or the amplification band width $\Delta\omega$ large. The low laser level must be not populated, that is, fast particle relaxation must be realized to the ground state. The lower laser state must be close to ground in order that the energy losses on relaxation be small. However, this energy interval must be several times higher than the thermal energy kT in order that there not be thermal population of the lower laser level.

The investigated active media (neodymium glass, gas mixture $CO_2$:$N_2$:He) are closer than the rest to satisfying these requirements, but they satisfy them far from completely. A third candidate for use in powerful devices is the iodine photodissociation laser (for $\lambda$ = 1.315 microns). The pumping of the iodine atoms into the metastable state is realized by photodissociation, for example, of the $CF_3I$ or $C_2F_5I$ molecules by ultraviolet (in the 275 nm range) radiation of a powerful flash tube. The photoabsorption band of these molecules is quite broad and provides for absorption of a noticeable portion of the flash tube energy. The energy stored in the excited iodine atoms reaches 25 joules/liter, and the time of existence of the energy reaches about 1 millisecond. At the present time a study is being made of the possibilities of this laser on multistage units with pulse energy in the nanosecond range of about 1 kilojoule. Such devices are in opeartion at the Physics Institute imeni P. N. Lebedev and the Plasma Physics Institute imeni M. Plank in Garching (Federal Republic of Germany).

Among the other investigated lasers it is necessary to mention the lasers based on the so-called eximer molecules (ArF, KrF, and so on, see item 4.5), the laser based on metastable oxygen atoms, and so on. However, their investigation still has not reached the level of creation of powerful lasers.

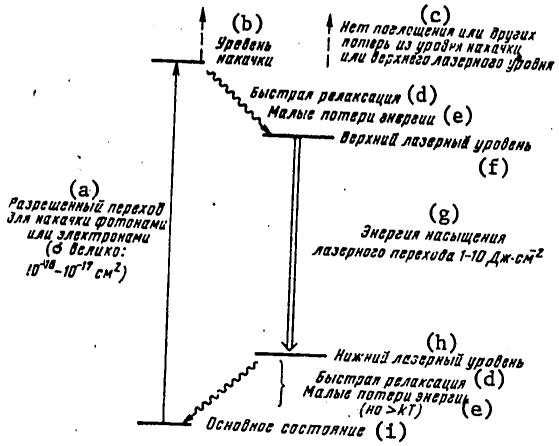


Figure 10. Quantum levels and pumping in generation transitions of a high power "ideal" laser.

Key:
a. permitted transition for photon or electron pumping (σ large:
b. pumping level
c. no absorption or other losses from the pumping level or
d. fast relaxation upper laser level.
e. small energy losses
f. upper laser level
g. saturation energy of laser transition 1-10 joules-cm$^{-2}$
h. low laser level
i. ground state

# 3. HIGH-POWER CONTINUOUS LASERS

## 3.1. Operating Principles of High-Power Continuous Lasers

For operation in the Continuous mode, a quite rigid requirement is imposed on the quantum system (atom, molecule or ion) of the laser: inversion of the level population must exist for a long time and not only in the transition, pulse mode. For this purpose the lower level of the operating transition of the quantum system must be depopulated quickly. Of course, this immediately limits the number of active media which can operate in the continuous mode. Nevertheless, many in practice important active media, for example, the $CO_2$:$N_2$:He mixture operate excellently in the continuous mode.

However, nevertheless, the most rigid requirements occur if it is required that the active medium generate sufficiently powerful radiation continuously. The removeal of heat from the core presents the greatest difficulty. Even for a laser with relatively high efficiency on the order of 10% with an output power of 1 kilowatt, 9 kilowatts of the pumping power are converted to heat. The thermal heating complicates the operation of the laser. First, during heating thermal excitation of the lower lying quantum levels of the quantum system occurs, which destroys the population inversion of the operating levels. Secondly, intense thermal heating distorts the optical uniformity of the active medium inside the resonator. Finally, strong thermal heating is capable of destroying the active medium itself -- thermally dissociating the molecular gas, melting glass or crystal. Therefore obtaining high power in the continuous mode is not only a complex scientific problem, but it also requires the solution of complex engineering problems. Even if the problem of selecting the appropriate quantum system with constant inversion of the level population is solved, a serious problem of fast heat release remains. This problem is, perhaps, the key problem of high-power continuous lasers similarly to how the nonlinear distortion and damage of the active medium by powerful laser emission is the key problem of the high-power pulse lasers investigated in the preceding item.

When using crystals or glass as the active medium, low thermal conductivity limits the generation power. For example, activated glass is entirely unsuitable for continuous generation even with a power level of tens of watts. Using crystals, for example, a YAG crystal with neodymium ions, as a result of the higher thermal conductivity, it is possible to obtain a continuous

generation power of about 100 watts. However, for generation on the 1 kilowatt level and higher only gas active media are suitable, independently of the pumping method. The gas mixture heated during pumping and generation can be chainged with fast pumping with a rate exceeding even the speed of sound. Therefore fast pumping of the gas mixture is at the base of all continuous high-power lasers: electric discharge, gas dynamic and chemical.

### 3.2. Electric Discharge $CO_2$-Lasers

The active medium of the highest-power (more than one kilowatt) electrodischarge lasers is exclusively the mixture of $CO_2$;$N_2$:He. In the first $CO_2$-lasers, glow discharge was used in long tubes with a pressure of several millimeters of mercury. The longitudinal discharge from the high-voltage dc source and comparatively slow flow of gas mixture along the tube were used. On optimization of the laser parameters it is possible to obtain a power of approximately 50-75 watts per meter of the gas discharge tube with an efficiency on the order of 10%. An increase in power is achieved by increasing the length of the active medium. Devices were created with a length of the active medium of several tens of meters having output power on the order of 1 kilowatt and even unique devices with output power to 10 kilowatts. One of such devices was created at the laboratory of academician of A. M. Prokhorov at the Physics Institute of the USSR Academy of Sciences. A photograph of it is presented in Figure 11. The output power of the device reaches 1 kilowatt with diffraction divergence of the radiation. A characteristic feature of this device is the wave guide propagation of the infrared beam in the small-diameter gas discharge tubes. This provides for formation of the laser beam with strictly fixed characteristics. These devices are of the greatest interest for physical experiments, in particular, for investigation of nonlinear phenomena in the infrared range where high spatial and time coherence of the laser beam is required.

When using fast transverse pumping of the gas mixture in transverse discharge such output powers can be obtained in much more compact lasers. In the lasers with a transverse cross section without output power of more than 1 kilowatt, two types of excitations are used: the independent discharge from the dc source with a gas pressure to 50 mm Hg and independent discharge where along with the dc source, an additional energy source is used which ionizes the gas mixture and facilitates uniform excitation of a denser gas mixture by the basic source of direct current. In practice all of the powerful continuous electric discharge lasers use one of these excitation methods. As a rule, independent discharge is used for lasers operating in the continuous mode with an output power to 10 kilowatts. The lasers with independent discharge are preferable for creation of systems with output power of more than 10 kilowatts.

The typical example of a powerful $CO_2$-laser using excitation by an independent discharge is the LT-1 experimental device with an output power to 5 kilowatts built at the Nuclear Power Intitute imeni I. V. Kurchatov in the laboratory of academician Ye. P. Velikhov. Its diagram is presented in

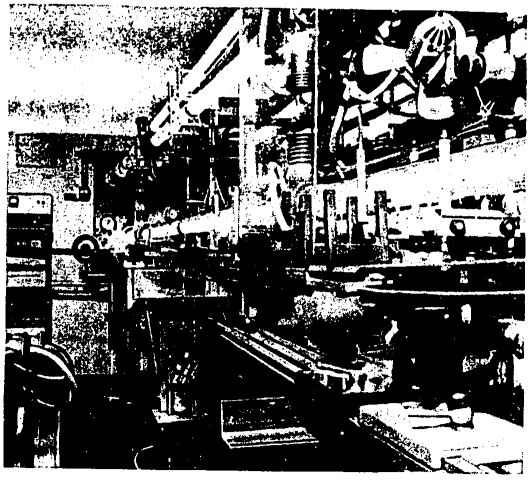

Figure 11. High-power wave guide continuous $CO_2$-laser generating a monochromatic beam with a power of 1 killowatt with gaussian intensity distribution in the transverse cross section created in the laboratory of academician A. M. Prokhorov at the Physics Institute imeni P. N. Lebedev of the USSR Academy of Sciences.

Figure 12. The device is a fast-flow electric discharge $CO_2$-laser with closed dynamic loop and transverse pumping. The gas dynamic loop is formed by a gas discharge resonator chamber. The gas discharge resonator chamber is illustrated in more detail in Figure 12,b. The flow rate of the gas mixture through the discharge chamber is 2-3 $m^3$/sec. As the working gas, the $CO_2$:$N_2$:He mixture is used in a 1:20:20 ratio with static pressure in the discharge chamber of 40-60 mm Hg. During operation of the laser, "poisoning" of the working mixture with the products of different plasma chemical reactions in the discharge chamber takes place unavoidably. Therefore constant partial replacement of the working mixture will be used (to fractions of a percentage of the total gas flow rate through the discharge chamber in one cycle). The heat exchanger with a heat pickup area of about 50 $m^2$ provides for cooling of the gas flow in a closed gas dynamic loop of the device with removal of the thermal power to 50 kilowatts.

It is possible to increase the output power of the electric discharge gas flow lasers by increasing the pressure of the gas mixture and the power contribution to it. In practice this can be done only by proceeding to the mode of independent burning of the discharge supported by an external ionizer. Above, in item 2.3 a study was made of pulse lasers with independent discharge. The transition to the continuous mode is not trivial, for serious technical difficulties arise for it: 1) fast overheating of the working mix by a continuous ionizer requiring pumping of the gas with

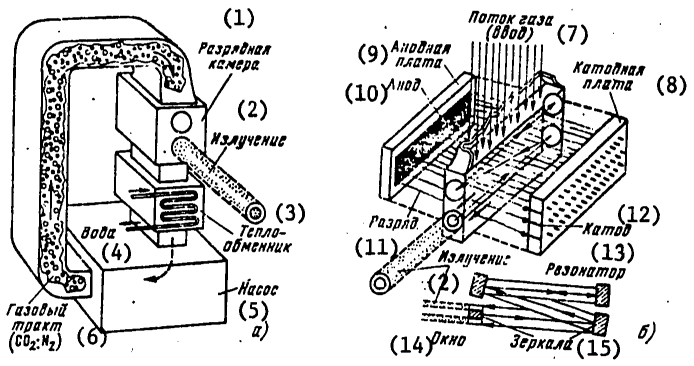


Figure 12. High-power, fast-flow continuous laser (LT-1 device) with a power of 5 kilowatts created in the laboratory of academician Ye. P. Velikhov at the Nuclear Power Institute imeni I. V. Kurchatov: a -- simplified form of the closed loop; gas mixture circulates; b -- structural design of a four-reflector resonator permitting the use of a significant volume of the active medium with small dimensions of each of the mirrors and an increase in the beam amplification as a result of an increase in the length of its propagation in the active medium.

Key:
1. discharge chamber
2. radiation
3. heat exchanger
4. water
5. pump
6. gas channel ($CO_2$:$N_2$)
7. gas flow (input)
8. cathode plate
9. anode plate
10. anode
11. discharger
12. cathode
13. resonator
14. window
15. mirrors

supersonic velocity, 2) short life of the thin foil through which a continuous strong-current beam of electrons is input from the vacuum chamber of the accelerator to the discharge chamber of the laser, and so on.

At the laboratory of academician Ye. P. Velikhov in the Nuclear Power Engineering Institute imeni I. V. Kurchatov, the possibility was demonstrated for uniform combustion of a stationary independent discharge with electron conductivity in the subsonic flow of gas at atmospheric pressure. This made it possible to create unique devices -- continuous $CO_2$-lasers -- with independent discharge with step-down power of the ionizer with an output power of the laser beam of tens of kilowatts.

3.3. Gas Dynamic Lasers

Gas dynamic lasers are a version of molecular gas lasers in which the energy source is the vibrationally excited molecules in a strongly heated gas, and

the amplification occurs as a result of the processes of relaxation of the excitation of the molecules during fast escape of the gas through a supersonic nozzle. Thus, the gas dynamic laser directly converts the thermal power to coherent radiation, being in this sense a unique instrument of quantum electronics. The operating principle of the gas dynamic laser is explained by Figure 13. The tricomponent gas mixture $N_2:CO_2:H_2O$ heated to a temperature on the order of 1500 to 1000 K escapes from the nozzle with supersonic velocity. Before the nozzle the gas mixture is in a thermodynamically equilibrium state. The basic component of the mixture (to 80-90%) is the $N_2$ molecules. They are a reservoir, a storage of thermal energy, for as a result of a long vibrational relaxation time they are capable of long term maintenance of vibrational excitation.

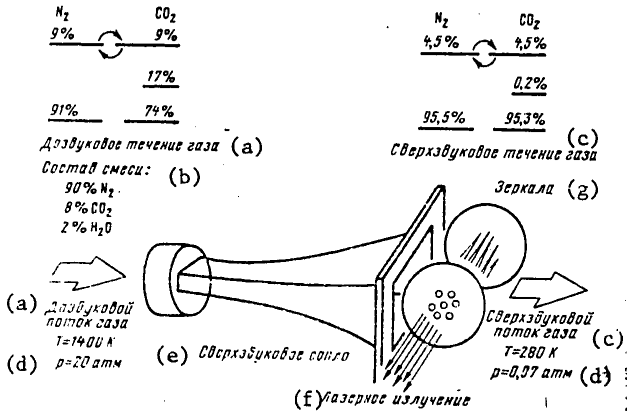


Figure 13. Explanation of the operating principle of gas dynamic lasers. The subsonic dense hot gas (a mixture of $CO_2:N_2$) is in thermodynamic equilibrium and, consequently, is not capable of amplifying radiation. The supersonic flux of cooled rarefied gas has population inversion of the vibrational levels of the $CO_2$ molecule; the $CO_2:N_2$ mixture is capable of amplifying and generating infrared radiation in the 10 micron range.

Key:
a. subsonic flow of gas
b. mixture composition
c. supersonic gas flow
d. atmospheres
e. supersonic nozzle
f. laser emission
g. mirrors

The expansion is accompanied by the conversion of the energy of random motion of molecules to the energy of directional motion of gas flow. This process takes place adiabatically without supplying heat. Therfore the energy of the thermal, random motion of the molecules decreases, and a low temperature (about 300° K) of translational and rotational movement of the molecules is

established in the supersonic flow. However, as a result of the prolonged time vibrational relaxation the $N_2$ molecules remain vibrationally heated.

The nonequilibrium state occurs thermodynamically. The vibrationally heated molecules are capable of resonance with high efficiency of transmission of the vibrational excitation to the $CO_2$ molecules which amount to 5-10% in the gas mixture. As a result, between the vibrational levels of the $CO_2$ molecules, population inversion and amplification occur in the vibrational-rotational bands in the range of 10.6 microns (Figure 3,b). The small admixture of water molecules (1-2%) insures rapid deactivation of the $CO_2$ molecules on the lower vibrational levels of the laser transition, that is, fast return of them to the ground state.

The population inversion and amplification of the $CO_2$ molecule occur in some range of gas flow which also is a fast-flow active medium. Here the output of the spent gas mixture which gives up the stored energy to the generated laser beam and input of a new lot of excited gas mixture are achieved automatically. Therefore the gas dynamic lasers have very high generation powers. Gas dynamic lasers with an output power of 60-100 kilowatts and an efficiency of approximately 1-2% were created and described in literature.

An important parameter of the gas dynamic lasers is the output power per unit mass of the consumed gas mixture. This parameter for various structural designs of the $CO_2$ gas dynamic lasers is within the range of 10-20 kilojoules per kg of gas mixture.

The gas dynamic laser with thermal excitation can be used as the base for a photon heat machine with closed cycle, the schematic of which appears in Figure 14. Here, just as in the investigated gas dynamic laser, the heated gas escapes from the nozzle system with supersonic velocity. An optical resonator is installed across the nonequilibrium-cooled gas flow in which generation occurs. The spent cooled gas mixture comes to the compressor which increases the gas pressure. The excess heat is picked up in the heat exchanger, and the newly heated dense gas is released to the nozzles. The operation of the photon heat machine is subject to the same laws of thermodynamics as the classical heat machines. The difference consists in the nature of the operating heat. In a photon heat machine which generates coherent radiation, the working medium has a discrete energy spectrum. The efficiency of the closed cycle photon machine, of course, must be higher than in the gas dynamic laser with single dispersion of the gas, inasmuch as the residual heat of the spent gas mixture is utilized in it.

In many laboratories, other versions of the gas dynamic lasers are being developed intensely. In the chemical-gas dynamic lasers for pumping the upper level, chemical reactions are used which are accompanied by the excitation of the vibrational levels. In the electrogas dynamic lasers, an additional electrical excitation of the expanding supersonic gas dynamic flow is used. A study is made of the possibility of creating high-temperature electrogas dynamic lasers in which at a temperature above 3500° K, a significant number of free electrons facilitating uniform excitation of the gas flow occurs as a result of thermal ionization.

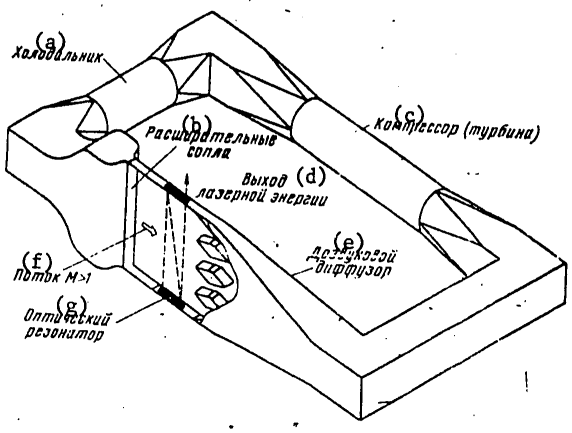


Figure 14. Closed cycle photon heat machine based on the use of the gas dynamic laser.

Key:
a. cooler
b. expansion nozzle
c. compressor (turbine)
d. laser energy output
e. subsonic diffusor
f. M > 1 flow
g. optical resonator

3.4. Chemical Lasers

The energy required for pumping in a chemical laser is supplied by a chemical reaction in the process of rearrangement of the chemical bonds. The first effective chemical laser was built in 1969 at the Chemical Physics Institute of the USSR Academy of Sciences by corresponding member of the USSR Academy of Sciences V. L. Tal'roze, et al., using the reaction of fluoridation of hydrogen. The reaction takes place between the $H_2$ molecule and the F atom:

$$H_2+F\rightarrow HF^*_v \quad (v=1, 2, \ldots)+H$$

as a result of which the energy $E_{chem.}$ = 31.7 kcal/mole is released, that is, about 1.3 ev per HF molecule. A significant proportion of this energy goes to the excitation of the vibrational levels (to v = 6) of the HF molecule between which population inversion occurs. In reality the mechanism of the reaction is more complicated, for it includes branching of the type of $HF^* + F_2 + HF + 2F$, $H_2^* + F_2 = H + HF + F$, and so on inasmuch as the chemical reaction of fluoridation of the hydrogen is a branched chain chemical reaction.

Figure 15,a gives the general diagram of a powerful continuous laser using the reaction of combustion of the fluorine with deuterium. It is made up of

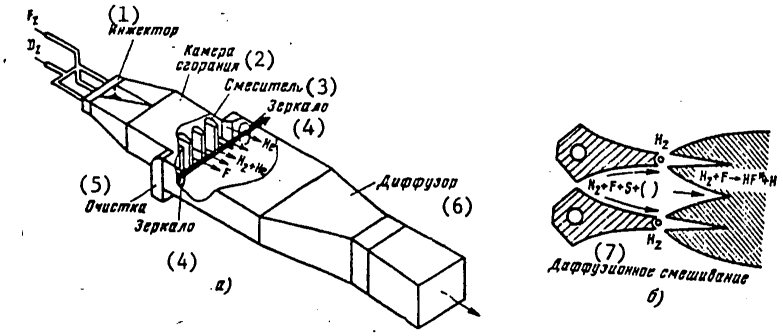


Figure 15. General diagram of a powerful continuous chemical laser using the reaction of the combustion of fluorine with hydrogen or deuterium (a) and the structural design of the diffusion mixer-nozzle (b).

Key:
1. injector
2. combustion chamber
3. mixer
4. mirror
5. purification
6. diffusor
7. diffusion mixing

the combustion chamber in which fluorine atoms are formed as a result of thermal dissociation of $F_2$. The hot atomic fluorine is passed through the nozzle and is thus cooled as in a gas dynamic laser. However, here the transmission through the nozzle is used only to cool the fluorine and for fast mixing of it with the hydrogen. In the mixer-nozzle shown in Figure 15,b, molecular hydrogen is continuously introduced into the cooled supersonic fluorine flow, and as a result of the chemical reaction of a cold fluorine atom with $H_2$, the vibrationally excited $HF^*$ molecules are formed.

In such a laser the inversion population density, the amplification and optical uniformity are well controlled. In devices of this type, the powers of continuous generation of 1-10 kilowatts are achieved on a wavelength of 3.6 microns on the DF molecule or 2.7 microns on the HF molecule. The chemical efficiency of such lasers reaches 10%. One hundred percent chemical efficiency corresponds to total conversion of the energy $E_{chem}$ released during the chemical reaction to coherent radiation. Since the HF laser radiation on a wavelength of 2.7 microns is strongly absorbed in the atmosphere by water vapor, the primary attention is given to DF chemical lasers, although they require more expensive deuterium for operation.

### 3.5. Prospective Continuous Laser Systems

Many laboratories are developing powerful electric discharge, gas dynamic and chemical lasers, the search for more effective molecules for them, the optimization of the laser parameters and improvement of the characteristics of continuous laser emission. However, the researchers are finding other methods of pumping continuous lasers which use more accessible, cheaper and

more powerful pumping sources. Unconditionally, the most prospective area here is the nuclear pumping of a laser, that is, the use of the energy of the fission products of nuclei in a reactor. Several years ago the researchers in the USSR (academician Ye. P. Velikhov, et al. at the Nuclear Power Engineering Institute imeni I. V. Kurchatov) and the United States (Los Alamos Scientific Laboratory and the NASA Laboratory) demonstrated the possibility of pumping a gas laser with neutrons from a nuclear reactor. For this purpose, helium-3 is added to the $CO_2$:$N_2$ gas mixture. The irradiation of the helium-3 with neutrons causes the formation of tritium nuclei and protons with the rate of energy sufficient for excitation of the gas mixture. The final goal of this research is the creation of a nuclear reactor, the active gas zone of which is a laser. For this purpose instead of solid state uranium rods, it is proposed that uranium hexafluoride molecules be used in the reactor. In this case even achievement of higher temperatures in the core is expected. The capture of a neutron by a uranium nucleus causes its fission with the release of about 200 Mev of energy in the fission fragments. The high-energy fragments are capable of exciting molecules in a gas mixture. Probably, it will be very difficult to obtain an inversion in the $UF_6$ molecule itself as a result of a large number of transitions having a tendency to "extinguish" the laser effect. Obviously, it is expedient to add another gas to the $UF_6$ as the laser medium. The estimates show that at the present time the most prospective lasers with nuclear pumping are chemical lasers based on mixtures of $UF_6 + H_2 + F_2$ and excimer lasers based on mixtures of $UF_6 + Xe + F_2$.

This approach promises the creation in theory of an autonomous, closed nuclear reactor-laser with high power in which direct conversion of the nuclear power to coherent light emission is realized without using any intermediate forms of energy (electric, light, chemical). If such a nuclear reactor-laser is built and has high efficiency, it can become an important part of the power engineering of the future. For example, when placed in space it can provide energy directly in space to space stations and to ships, it can insure directional transportation of energy in the form of a powerful laser beam to cosmic distances. It is especially valuable that such nuclear reactor lasers can be placed outside our habitat on earth, which greatly simplifies the problem of getting rid of radioactive waste. The areas of development of powerful continuous lasers which promise the inclusion of powerful lasers as elements for the conversion and transmission of energy in the power engineering of the future appears to be especially prospective today.

## 4. POWERFUL PULSE-PERIODIC LASERS

### 4.1. Operating Principle

For many applications of laser radiation it is necessary to combine high peak power (on the order of a megawatt or more) and significant average power of the radiation (from hundreds of watts to tens of kilowatts). A standard example of such an application is separation of the isotopes by selective dissociation of the molecules by powerful infrared radiation. The molecule dissociates usually with a pulse power of no less than $10^6$ watt/cm$^2$, and for dissociation of a quite large number of molecules per unit time, that is, to obtain high output capacity of the process, high average power is required (1 to 10 kilowatts and more). For this purpose periodic-action pulse lasers are being developed which emit light pulses with an energy from fractions to tens of joules with a repetition frequency from tens of hertz to tens of kilohertz. High peak power of such lasers imposes defined requirements on the radiation strength of the active medium and the laser elements to some degree resembling the requirements characteristic of powerful monopulse lasers. However, high average power causes difficulties which are typical of continuous systems: thermal heating of the active medium and elements of the laser. The pulse-periodic lasers with high medium radiation power have their specific difficulties, for example, realization of reliable periodic commutation of high powers reaching hundreds of kilowatts in individual cases.

Generally speaking, the pulse-periodic lasers are based on the following two general approaches. The first approach uses continuous pumping of the active medium of the laser with periodic control of the process of its generation. This approach can be realized for any active medium having an excitation accumulation time of the same order or higher than the time interval between the pulses. This is done simplest of all by periodic modulation of the Q-factor with a frequency equal to the recovery time of the working medium after generation of the next pulse to the inverted state under the effect of continuous pumping. The operation, for example, of the YAG:$Nd^{3+}$ crystal lasers is based on this principle. In this case, it is not necessary to switch the high pumping power of the laser periodically. Unfortunately, for the majority of active media the inversion accumulation time during continuous pumping is much less than the required interval between laser pulses.

For example, in the gas mixture $CO_2$:$N_2$:He with a total pressure of 1 atmosphere the time of existence of the inversion is equal to 20 microseconds, and consequently, for complete use of the energy of continuous pumping the pulses must have a repetition frequency of about 50 kilohertz. With a defined average power, for example, 1 kilowatt, the energy of one pulse of such a laser will be a total of 0.02 joules. Therefore this approach is effective only for the generation of pulses with relatively low energy and peak power but with high repetition frequency of them.

A more universal and widespread approach is the pulse-periodic pumping of the laser when the pules repetition frequency either is dictated by the conditions of application of the radiation or it is limited by the thermal effects in the active medium of the laser or even in its elements (the discharger, thyratron) commuting the pumping power periodically. With this approach it is possible to create comparatively high energy and power of one pulse with the repetition frequency required for many applications (usually from single hertz to tens of kilohertz).

In the pulse-periodic lasers with an average power of more than 100 watts, fast pumping of the active medium (a gas mixture or working liquid) is always used to remove the released heat. For this reason lasers based on luminescent crystals and glass, semiconductors and so on are inapplicable here. As standard and important examples, a study is made below of a gas discharge pulse laser based on metal vapor, the gas discharge pulse molecular laser and pulse laser based on a die solution with optical pumping. In all of these cases, pulse generation is demonstrated with an average power of about 100 watts, and there are grounds for a further increase in it into the 1 kilowatt range or higher.

## 4.2. Electric Discharge Lasers Based on Atoms

The pulse gas discharge lasers represent a large class of lasers operating on the quantum transition atoms, molecules and ions. The flexibility and universality of the electric discharge pumping consists in the possibility of fast loss of equilibrium for a short time, to nanosecond intervals, distribution of the particles with respect to quantum levels. This time in many cases is shorter than the recovery time, that is, the relaxation of the particle distribution with respect to quantum levels to the equilibrium Boltzman distribution. Therefore in a short in some transitions of any atom, molecule or ions it is possible to obtain inverse population levels and amplification of the frequency of the radiation transition between them.

In the discharge in an atomic gas the basic energy is expended by electrons on excitation of the first resonance level of the atoms. It is known, for example, that under certain conditions up to 60% of the energy introduced into the discharge is spent on excitation of the first resonance level of mercury. The first resonance level of the atom usually has the largest excitation cross section by the electrons (on the order to gas kinetic, that is, $\sigma_{exc} \approx 10^{-16}$ cm$^2$). The excitation of the rate of the atom by the electrons $W_{exc}$, that is, the probability of excitation of an atom per unit time,

is determined by the simple expression, $W_{exc} = n_e < \sigma_{exc} v_e >$, where $n_e$ is the electron concentration in the discharge; $v_e$ is the electron velocity; the brackets denote averaging of the excitation cross section $\sigma_{exc}(v_e)$, which depends on the electron velocity, with respect to the electron velocity distribution. For standard values of the parameters ($\sigma_{exc} = 10^{-16}$ cm$^2$, $n_e = 10^{15}$ to $10^{16}$ cm$^{-3}$, $v_e = 10^8$ cm/sec) it is possible to achieve high excitation rates $W_{exc} \approx 10^7$ to $10^8$ sec$^{-1}$. For many atoms (Cu, Pb, Tl, Mn and so on) one metastable level (sometimes several) is located between the ground and the first resonance levels (see Figure 16), which is not excited on collision of an atom with electrons or photons. During the first instants of discharge, this level continues to remain unpopulated at the same time as the higher-lying resonance level is strongly populated with electrons. Therefore during the first nanoseconds of pulse discharge in the vapor of many metals, population inversion of the first resonance level and the lower-lying metastable level occurs. Generation on such a transition must have a pulse nature inasmuch as after simulated transition of the atom from the excited state to the metastable state, population inversion disappears. Only after discharge extinguishes not all of the atoms return to the ground state can the process again repeat.

One of the most prospective lasers of this type is the copper vapor laser. With a temperature of about 1500° C, the copper vapor pressure reaches fractions of a millimeter of mercury. First, it is very difficult to maintain such a high temperature in the discharge tube. Therefore frequently copper salt vapor is used (for example, copper iodide), which requires heating to more moderate temperatures (on the order of 400° C). Generation occurs on two wavelengths (5106 and 5782 Å) corresponding to the transitions of the excited atom to two similar metastable states. In the gas discharge tube 5 cm in diameter and about 1 meter long, a peak power of about 40 kilowatts is achieved with a pulse duration of 15-20 nanoseconds and an efficiency of more than 1%. With a pulse repetition frequency on the order of 10-100 kilohertz, the average power of each is several tens of watts. It is necessary to pay attention to high generation efficiency on the green line of the copper. None of the other gas lasers in the visible range of the spectrum has efficiency of more than 1%. In practice with careful optimization of the laser parameters, including the system for obtaining copper vapor and excitation of it, an efficiency of 2-3% is entirely admissible.

New work is being done in a number of laboratories to increase the average power of such a laser to 100 watts to 1 kilowatt. This, of course, is possible only under the condition of a fast exchange of the working gas in the discharge tube. Fast pumping of the He:Ar:Cu mixture with supersonic velocity permits changing of the working mixture in the generation region having transverse dimension of 2-3 cm in 10-20 microseconds. This makes it possible to increase the pulse repetition frequency to 50 kilohertz. An energy of 1 pulse is determined by the generated volume, for the standard specific energy pickup is limited to a value of several joules per cubic meter.

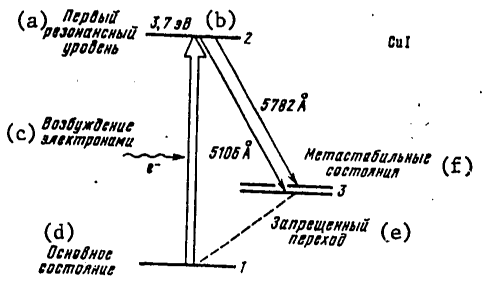


Figure 16. Diagram of the pumping (electron excitation) and generation transitions in the electric discharge pulse-periodic laser based on copper vapor.

Key: a. first resonance level
b. 3.7 ev
c. excitation by electrons
d. ground state
e. forbidden transition
f. metastable state

It is possible to expect further progress of this laser system, in particular, based on copper, lead and other vapor and to expect application of it as a coherent source with a high average power for pumping powerful dye lasers with tunable frequency.

4.3. Electric Discharge Molecular Lasers

The high average powers still can be obtained only in the molecular transitions of the molecules in the infrared band. The best results were obtained for the pulse-periodic $CO_2$ molecular laser. Let us only consider the peculiarities which are characteristic of the pulse-periodic laser with an average power of 1 kilowatt or more. The special design of such a laser developed at the branch of the Nuclear Power Institute imeni I. V. Kurchatov in the laboratory of academician of Ye. P. Velikhov is shown in Figure 17. The gas flow required to replace the working mixture heated in the discharge is created using a compressor with an output capacity of 300 liters/sec. Two coolers and the discharge chamber of the laser were installed in the gas channel. A grid for equalizing the gas flow rate profile was installed in front of the electrode system of the laser with transverse electric excitation. For creation of the pulse volumetric discharge, the electric discharge system is used with preliminary ionization of the gas by ultraviolet radiation of the spark channels located downstream with respect to the shaped operating electrodes. The preionization energy is less than 5% of the energy included in the basic discharge plasma.

The standard parameters of the laser with an average power of 1 kilowatt are as follows: the volume of the discharge region V = 0.6 liters, the length along the resonator axis L = 60 cm, the gas flow rate in the region between

the electrodes $v_0$ = 30 m/sec, the nonuniformity of the velocity with respect to width is no more than 10%. The feed for the discharge chamber of such a laser is realized by current pulses with a front buildup time of 100 nanoseconds and a duration of 1 microsecond with a current amplitude of 50 kiloamps and an initial voltage on the low-inductive capacitor to 30 kilovolts. In order to insure multihour continuous operation of the laser, partial renewal of the gas mixture was realized ($CO_2$:$N_2$:He or $CO_2$:He) with a rate of about 1% of the total gas flow, that is, about 3 liters/sec. The laser operates persistently at pressures of the working mixture in the loop to 0.8 atmospheres. With energy contribution to the volumetric discharge of about 300 joules/liter-atmosphere the energy in one generation pulse reaches 6 joules, and a repetition frequency reaches 200 hertz. The laser efficiency is 10%. The operating cost per 1 hour of the laser defined primarily by the cost of the irretrievably lost helium on renewal of the mixture is 60 rubles. However, with careful execution of the closed loop it is possible significantly to reduce the helium consumption and decrease the cost of 1 hour of operation of the laser to several rubles.

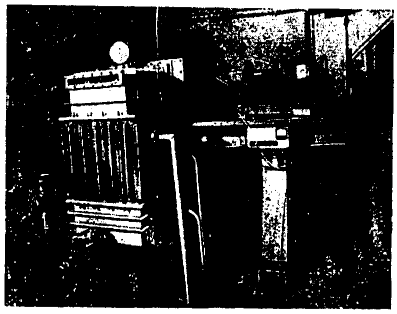

Figure 17. Overall view of the pulse-periodic $CO_2$-laser with average power of 1 kilowatt and selection of the vibrational-rotational transitions in the range of 9.2 to 10.8 microns (the "Dyatel" device) created in the branch of the Nuclear Power Institute imeni I. V. Kurchatov.

The theoretically maximum repetition frequency of the pulses is determined by the pumping time of the gas through the discharge gap, that is, the value of $f_{max} = v_0/b_0$, where $v_0$ is the pumping rate of the working mixture; $b_0$ is the electrode width. This corresponds to the maximum average power of the laser $P_{max} = \mathcal{E}_0 f_{max}$ where $\mathcal{E}_0$ is the energy of one pulse. In the described laser the maximum average power is reached for pulse repetition frequencies 5 times lower than the maximum frequency of $f_{max}$. With a further increase in the pulse repetition frequency, a proportional drop in the energy of each pulse takes place. This limitation of the repetition frequency of the pulses is connected with nonuniformities of the gas density remaining in the discharge gap by the next pulse. The electrode system with ultraviolet preionization

of the gas is highly sensitive to the density nonuniformities occurring in the gas flow during pulse flow of the current which lead to arc formation during the next discharge pulse. The occurrence of the nonuniformities arises from an increase in energy relief in the discharge layers next to the electrodes and the shock waves formed as a result of it. Accordingly, the renewal of the gas in the electrode regions turns out to be less effective than in the central discharge regions.

The principles of creating powerful pulse-periodic $CO_2$-lasers are also applicable to the laser on the oscillatory transitions of other molecules, for example, $N_2O$, CO, DF, and so on. It is true in each such case that it is necessary to study and solve the problem of closed gas circulation through the discharge chamber separately, for the partial renewal rate of the gas mixture of each type depends on the decomposition rate of the initial molecules, the composition of the products formed, and so on. As for the pulse-periodic $CO_2$-lasers themselves, obviously their average power can be brought entirely to 10 kilowatts while maintaining a quite high operating reliability and controlled parameters of the output beam. This power level is necessary to develop new technological processes, in particular, laser separation of the isotopes by selective dissociation of the molecules by powerful infrared radiation pulses.

4.4. High-Power Tunable Dye Lasers

For the selective effect of laser radiation on matter (separation of the isotopes, obtaining pure materials, stimulation of chemical reactions), lasers are needed with a tunable wavelength in the visible and ultraviolet bands with high average power (100 watts to 1 kilowatt or more) and good reliability. It is necessary to emphasize that the problem of creating the frequency-tunable lasers is up to now one of the central problems in quantum electronics. Thousands of scientists and engineers in many laboratories in a number of countries are working on its solution. At the present time the set of methods of generation of tunable radiation based on the basic ideas of quantum electronics and nonlinear optics are found and successfully used.

One of the universal methods of creating tunable lasers is the use of active media with wide amplification lines which permit generation of many frequencies. Then by selection, that is, frequency tuning of the maximum Q-factor of the resonator, it is possible to achieve generation on any frequency within the limits of the broad spectral amplification line. This is how the tunable lasers operate in the ultraviolet, visible (molecular dye solution lasers) and infrared (semiconductor lasers) regions of the spectrum. Among them a special role is played by the dye lasers developed by scientists of the USSR, the United States and the Federal Republic of Germany. This principle of dye lasers is obviously explained by their simplicity, universality, broad application and, what justifies their discussion in the given brochure, the possibility of obtaining a comparatively high average power. The basic method of creating such lasers consists in powerful optical pumping of the dye solution. Two approaches are used here: 1) pumping with powerful sources of coherent radiation, for example, a pulse copper vapor laser investigated in the preceding item and 2) pumping with powerful pulse tubes.

With laser pumping as a result of higher efficiency of the use of the coherent pumping radiation (10 to 30%) and ease of focusing of the radiation it is easier to solve the problems of rapid pumping of the dye solution, obtaining high uniformity of the output laser beam and controlling its wavelength. This approach now is being developed intensely inasmuch as by using it, it is entirely realistic to create lasers with tunable wavelength of average power on the order of 100 watts and the repetition frequency of the laser pulses of 10 to 50 kilohertz. The last parameter is especially important for laser separation of isotopes in atomic beams, for the period between the series laser pulses (20 to 100 microseconds) is becoming comparable to the drift time of the atoms through the laser beam and, consequently, it is possible to extract the entire target isotope from the atomic beam, not transmitting the atoms without interaction with the laser beam. Of course, the overall efficiency of such lasers with binary pumping energy conversion (the discharge → pulse of coherent pumping radiation → pulse of coherent dye radiation) is low, and it is defined by the product of the pumping laser efficiency and the dye laser efficiency. In the best case it is 1%, and usually 0.1%.

When pumping the dye solution directly by the incoherent radiation of flash tubes, in addition to the general problems for dye lasers (rapid pumping of the dye, maintenance of optical uniformity with pulse powerful pumping, photodegredation of the dye molecules) the greatest difficulty is presented by the creation of a flash tube with large operating reserves. If the flash tube has a reserve of 1 million flashes, then with a pulse repetition frequency of 100 hertz it fails approximately after 3 hours of continuous operation. However, the importance of the problem of creating powerful tunable lasers is so great that the researchers of a number of countries are developing a key element of such a laser -- the flash tube with a reserve of up to 100 million flashes -- and special effective dye radiation systems by such tubes. As a result, two types of dye lasers have been created with an average power of 100 watts and repetition frequencies of 50 to 250 hertz.

The basic mechanisms of the destruction of the flash tube are evaporation of the walls of the gas discharge tube and the effect of the shock wave on the tube walls. In order to eliminate these phenomena, fast blowing through the discharge tube of a vortex-stabilized gas flow is used through which the current pulse is passed. This vortex flow does not touch the walls of the tube and destroys them to a much lesser degree. The radiation of the gas vortex discharge is collected on the surface of the couvette with the dye in a spherical mirror chamber.

When using several less powerful flash tubes for pumping, more complex illumination systems are used. One such system of a powerful dye laser created by one of the inventors of dye lasers, professor F. Schaefer in the Federal Republic of Germany is shown in Figure 18. In all of the powerful lasers, fast pumping of the dye solution is necessary. The repetition frequency of the pulses essentially depends on the rate of pumping the dye, for only after disappearance of nonuniformities in the active medium occurring under the effect of a pumping pulse is it possible to feed the next pulse. In order to

decrease the photochemical destruction of the dyes from pumping light using filters, ultraviolet radiation is eliminated which does not play a role in the excitation of the working (laser) levels of the dye molecules, but it excites high electronic states, involving molecules in the photochemical conversions. The total efficiency of the lasers with tube pumping reaches values of 0.3 to 0.4%.

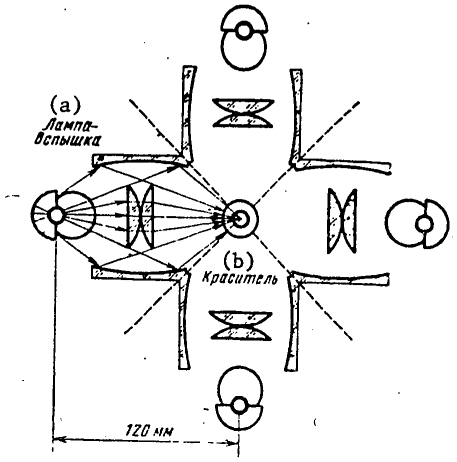


Figure 18. Structural design of a complex illuminator for a powerful dye laser with pumping by several flash tubes.

Key: a. flash tube b. dye

The successful creation of dye lasers with an average power of 100 watts has made it possible to surmount the next power parrier -- the creation of dye lasers with tunable frequency in the visible range with an average power on the order of 1 kilowatt.

4.5. Prospective Laser Systems

Among the most promising laser pulse-periodic systems with high power it is necessary to isolate the class of lasers based on so-called excimer molecules which potentially make it possible to encompass the entire ultraviolet band and significant regions of the vacuum ultraviolet, that is, the region from 1000 to 4000 Å. The excimer molicules are molecules which exist only in the excited electron state. On emission of a quantum of light, the excimer molecule goes into the lower ground state which decays in a very short drift time of the atoms ($\approx 10^{-13}$ sec). The standard examples of excimer molecules are inert gas molecules and their compounds ($Xe_2$, $Ar_2$, ArF, KrF, and so on).

The first excimer laser was proposed and created at the laboratory of academician N. G. Basov at the Physics Institute imeni P. N. Lebedev of the USSR

Academy of Sciences, where generation was obtained in 1970 on the $Xe_2$ excimers ($\lambda$ = 176 nm) with excitation of the liquid xenon by a high-current beam of fast electrons.

In 1974 several of the American laboratories, the laser effect on excimer molecules which are unstable compounds of a noble gas atom with a halide atom (ArF, XeF, KrF, XeCl, XeBr, and so on) was detected. The mastered range of generation wavelengths of this class of excimer lasers extends from 175 (ArCl) to 354 nm (XeF), and further mastery of the generation range is expected both in the shortwave region to 107 nm (NeF) and in the visible range. It turned out that in addition to the fast electron pulse, the effective excitation of excimer lasers under a pressure of a gas mixture of several atmospheres is possible by fast pulse discharge and also combined discharge with preionization of it by a beam of fast electrons. The efficiency of the excimer lasers with electron and combined pumping reaches 10% (with an electron beam energy of 2000 joules on the ArF molecule a radiation pulse was obtained in the vacuum ultraviolet with an energy of 200 joules). When pumping with fast electric discharge the efficiency is in the range of 1% with significant simplification of the structural design of the laser. At the present time conditions have been realized for high pulse repetition frequency as a result of fast pumping of the working gas mixture. It is also important to note that the relatively broad amplification lines of the excimer molecules will permit adjustment of the generation wavelength by several tens of angstroms. It is possible to predict further fast development of the pulse-periodic high-power lasers in the ultraviolet and vacuum ultraviolet regions of the spectrum on excimer molecules.

## 5. NONLINEAR OPTICAL PHENOMENA

The first powerful lasers generated light pulses with a power on the order of megawatts. When focusing such pulses it was immediately possible to observe new nonlinear optical phenomena: the generation of harmonics, parametric conversion of frequency, illumination of the absorbing medium, optical breakdown of the gas, and so on. Let us note that many of the nonlinear optical phenomena were discovered and studied by academician R. V. Khokhlov and professor S. A. Akhmanov, et al., who created the Soviet school of nonlinear optics. Whereas it was necessary to state highly complex experiments previously to observe nonlinear optical phenomena, at the present time the situation has changed. The modern powerful lasers generate coherent radiation of such high power that it is limited primarily to the nonlinear interaction of light in the optical elements of the device entirely transparent from ordinary light. The designer of powerful lasers must taken into account the nonlinear effects in glass, crystals and other elements even in elementary engineering calculation.

Thus, power laser radiation at the dawning of quantum electronics led to the birth of nonlinear optics, and now progress in obtaining power emission is determined to a great extent by the development of optical elements with the least nonlinearity in a strong light field.

The nonlinear phenomena are being widely used to expand the range of frequencies of powerful lasers and to obtain smooth frequency tuning. The progress in this region is determined to a significant degree by the search for materials with high nonlinearity coefficients. As a rule, these materials are single crystals. The development and the mastery of the procedures for obtaining quite large single crystals with high optical quality constitute an important are of quantum electronics. Our scientific research and industrial organizations have mastered the manufacture of nonlinear high quality elements. The application permits us to obtain the second, third and fourth harmonics of the basic laser emission with high efficiency and also to create parametric generations with smooth frequency tuning. Already at the present time the basic areas of application of nonlinear phenomena have appeared in the field of powerful laser emission:

1. The generation of the harmonics, the summary and difference frequencies for expansion of the range of wavelengths of coherent radiation.

2. Parametric generation of tunable radiation in nonlinear crystals proposed and successfully realized by scientists of the USSR (R. V. Khokhlov and S. A. Akhmanov, et al.) and the United States (D. Dzhordmeyn and R. Miller). In this case the frequency of a powerful laser field as a result of nonlinearity of the interaction with the crystal splits (is divided) into two frequencies where the point of their splitting is regulated by the crystal itself (its orientation, temperature).

3. Up-conversion or nonlinear transformation of the radiation upward with respect to frequency. In this case the infrared photon is summed in a nonlinear crystal with powerful visible radiation, and in this way it falls in the visible region where there are very effective photoreceivers. As a result of such nonlinear rransformation of the frequency it is even possible to visualize invisible infrared images. This area is one of the most urgent in applied nonlinear optics.

5.1. Strong Light Field

Focusing the laser beam of even moderate power, it is possible to obtain high intensities of the light field. Let us consider for determinacy the light beam of an improved laser generating $TEM_{00}$, that is, the basic type of oscillations having bell-shaped intensity distribution in the transverse cross section (Figure 19) and an almost plane wave front. From the point of view of such conversion in subsequent optical systems the so-called "gaussian" light beam is ideal, the transverse (radial) distribution of the intensity of which is described by the gaussian distribution:

$$I(r)=I_0 exp(-r^2/w_0^2), \tag{5.1}$$

where $I_0$ is the radiation intensity (watts/cm$^2$) at the center of the distribution, $2w_0$ is the light beam diameter measured with respect to the level of decay of intensity by $e^2$ times, that is, by the level of 13.5% intensity at the maximum.

Any light of limited diameter has finite angular divergence as a result of diffraction. The gaussian beam has minimum divergence of $2\theta_{diff}$, where

$$\theta_{\text{диф}}=\frac{1}{\pi}\frac{\lambda}{w_0}. \tag{5.2}$$
(a)

Key: a. diff

The brightness of the gaussian light beam $B_0$ (watts/cm$^2$-sec) is defined by the expression $B_0 = I/\Omega$, where $\Omega$ is the solid angle in which the light beam is concentrated. The gaussian beam with small divergence ($\Omega = \pi\theta^2_{diff} << 1$) has brightness of

$$B_0 = I_0 \pi (w_0/\lambda)^2 = I_0 (S_0/\lambda^2), \tag{5.3}$$

where $S_0 = \pi w_0^2$ is the effective area of the transverse cross section of the beam in which 98% of the radiation energy is concentrated. In many cases as a result of nonuniformity of the active medium, imperfection of the resonator and so on the laser generates many transverse types of oscillations ($TEM_{mn}$, m, n >> 1), the transverse intensity distribution of which is strongly nonuniform by comparison with the gaussian distribution (5.1). The divergence of such a light beam is correspondingly greater than the minimum diffraction divergence (5.2), and the brightness is less than the maximum possible value of (5.3).

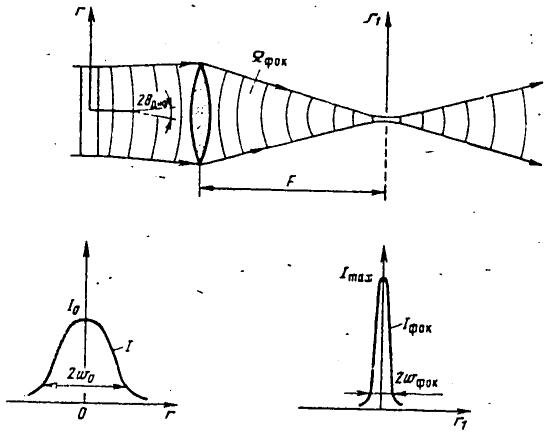


Figure 19. Increase in power of the light field by focusing a spatially coherent light beam.

Key: a. $\Omega_{foc}$ b. $I_{foc}$ c. $w_{foc}$

When focusing the gaussian beam by a good quality lens, that is, an aberrationless lens, a spot appears at the focal point with gaussian distribution of intensitive

$$I_{\text{фок}}(r_1) = I_{max} \exp(-r_1^2/w^2_{\text{фок}}), \tag{5.4}$$

(a)

Key: a. foc

where $I_{max}$ is the intensity at the maximum, and the effective diameter of the focal point $2w_{foc}$ is connected with the initial diameter of the gaussian

beam $2w_0$ and the focal length of the lens F by the expression

$$w_{фок} = \frac{1}{\pi}\frac{\lambda}{w_0}F. \tag{5.5}$$

The maximum intensity of the focal point of the lens $I_{max}$ with respect to the areas of the transverse cross section of the input and the focused beams $(S_0/S_{foc})$ exceeds the intensity of the input beam $I_0$:

$$I_{max} = I_0(w_0/w_{фок})^2. \tag{5.6}$$

The focused beam occupies a solid angle of $\Omega_{foc} = \pi(w_0/F)^2$. Hence, it follows that the brightness of the light beam with focusing $B_{foc} = I_{max}/\Omega_{foc} = B_0$, that is, it remains unchanged, for the decrease in transverse cross section of the beam is accompanied by a proportional increase in its solid angle. This statement, as is known, is the content of one of the fundamental theorems of geometric optics which says that for any transformations of a light beam by optical systems its brightness $B_0$ does not change.

The brightness of the light beam is connected with its other important characteristic -- the effective temperature $T_{eff}$ which is defined as the temperature of an absolutely black body with energy brightness equal to the brightness of the laser beam:

$$\underset{(a)}{B_{лаз}} = \underset{(b)}{B_{черн.тела}} = \underset{(c)}{(1/\pi)\sigma T^4_{эфф}}, \tag{5.7}$$

Key: a. las b. black body c. eff

where $\sigma = 5.67\cdot10^{-12}$ watts/(cm$^2$-sec) (deg)$^4$ is the Stefan-Boltzmann constant. When it is said that the laser emission has high effective temperature, let us say, $T_{eff}$ = 10 million degrees (the standard temperature of thermonuclear combustion, which exceeds by a thousand times the radiation temperature of the surface of the Sun -- the natural thermonuclear reactor), this reflects the basic property of the spatially-coherent laser beam -- high angular concentration of the light field, that is, high brightness. The ordinary light sources scatter their emission isotropically, and in spite of the high total radiation power they have low brightness and low effective emission temperature. The basic correlaries from the simple relation (5.7) will be considered in the following item which takes up the high-temperature heating of matter by laser emission.

Table 2. Characteristics of powerful laser pulses (power $10^{12}$ watts, effective diameter of the gaussian beam $2w_0$ = 30 cm, focal length of the lens F = 50 cm)

| Characteristics | Neodymium glass laser, λ = 0.6 microns | | $CO_2$ laser, λ = 10.6 microns | |
|---|---|---|---|---|
| | direct beam | at focal point | direct beam | at focal point |
| Intensity, watts/cm$^2$ | $1.4\cdot10^9$ | $2.5\cdot10^{19}$ | $1.4\cdot10^9$ | $2.5\cdot10^{17}$ |
| Brightness, watts/(cm$^2$-sec) | $8.8\cdot10^{19}$ | | $8.8\cdot10^{17}$ | |
| Effective temperature, ° | $8.36\cdot10^7$ | | $8.64\cdot10^7$ | |
| Electric field intensity, volts/cm | $7.3\cdot10^5$ | $9.7\cdot10^{10}$ | $7.3\cdot10^5$ | $9.7\cdot10^9$ |
| Magnetic field intensity, gauss | $2.4\cdot10^3$ | $3.2\cdot10^8$ | $2.4\cdot10^3$ | $3.2\cdot10^7$ |
| Electromagnetic energy density or light pressure, bars (or atmospheres) | 4.7 | $8.3\cdot10^9$ | 4.7 | $8.3\cdot10^7$ |
| Kinetic energy of electrons, ev | $1.47\cdot10^{-4}$ | $1.5\cdot10^6$ | $1.47\cdot10^{-2}$ | $1.5\cdot10^6$ |

Intensities of the electric field E and magnetic field H are defined by the expression $H = E = (4\pi I/c)^{1/2}$. Table 2 gives the characteristics of the laser emission of the two most powerful laser systems: the neodymium glass laser which emits a pulse with an energy of 1 kilojoule lasting 1 nanosecond and a diameter of the light beam of 30 cm on a wavelength of λ = 1.06 microns; a carbon dioxide laser which emits the same pulse on a wavelength of λ = 10.6 microns. In the table the values of the parameters are presented both by the direct and the unfocused beam and at the focal point of an ideal lens. For comparison let us present the intensity of the electric field of a hydrogen atom at a distance of 1 Bohr radius $a_0$ from the nucleus

$$E_{ат}=e/a_0^2=5{,}2\cdot10^9 \text{ volts/cm.} \qquad (5.8)$$

The light field intensity at the focal point of the powerful laser beam can greatly exceed the characteristic intensity of the intraatomic field for a light atom. The intensity of the magnetic field is also very high; at least it naturally exceeds the highest intensities achieved by the method of magnetic explosion cumulation.

Table 2 gives the values also of other characteristic parameters of a strong light field frequently used when analyzing the interaction of the light field with the medium. The density of the electromagnetic energy u is

$$u = I/c, \tag{5.9}$$

This value determines the light pressure of the laser beam on the surface of the matter completely absorbing the radiation. For the presented numerical examples, the short term light pressures are so high that they cause strong macroscopic mechanical effects, which is quite unusual for a light field of incoherent sources. Another characteristic parameter of the strong field of the focused light beam is the average kinetic energy of the electron oscillations $\mathscr{E}_{kin}$ in a periodic electric field. Its magnitude is defined by the expression

$$\mathscr{E}_{\text{кин}}=e^2E^2/2m\omega^2=e^2I\lambda^2/2\pi mc^3, \tag{5.10}$$

(a)

Key: a. kin

where m is the electron mass; $\omega = 2\pi c/\lambda$ is the light oscillation frequency, rad/sec.

Table 2 gives the values of the parameters for record (the most powerful) lasers created for investigation of laser thermonuclear fusion. However, it must be noted that the intensities $10^2$ times less are entirely available today for any well equipped laboratories, and intensities of $10^3$ to $10^4$ times are attainable using commercially available lasers, that is, for any scientific laboratory.

## 5.2. Effects of a Powerful Light Field

A powerful light field interacts with matter essentiall nonlinearly. A large number of large nonlinear optical effects have been predicted and detected which are manifested for the most different light intensities depending on the mechanism of interaction of the light field with matter. The resonance interaction of the light with the atoms and molecules become nonlinear for comparatively low intensities. The nonresonance interaction becomes nonlinear in fields, the intensities of which depend on the energy of the photons and the characteristic energies of the elementary interaction process. For example, multiphoton ionization of atoms requires high, but entirely attainable intensities, and multiphoton generation of electron-positron pairs is possible only in exceptionally powerful light fields, the obtaining of which is still problematic. Let us briefly enumerate the nonlinear effects and let us indicate the light field intensities for which they become noticeable.

Absorption Saturation. The noticeable population of excited atomic, molecular or ion levels under the effect of a resonance light field occurs for such intensities where the speed of the induced transitions $W_{ind}$ becomes comparable wiht the level population relaxation rate to the equilibrium state, that is,

$$W_{\text{инд}} = \sigma_{\text{рез}} I/\hbar\omega_0 \gtrsim 1/T_1, \tag{5.11}$$
(a) (b)

Key: a. ind b. res

where $\sigma_{res}$ is the cross section of the resonance induced transition between levels; $T_1$ is the level population relaxation time of the resonance transitions; $\hbar\omega_0$ is the transition energy. Thus, the saturation of absorption, that is, transillumination of the absorbing transition, takes place at intensities which satisfy the condition

$$I \gtrsim I_{\text{нас}} = \hbar\omega_0/\sigma_{\text{рез}}T_1. \tag{5.12}$$
(a)

Key: a. sat

For the permissible transitions of the atoms in the optical range $\sigma_{res} = 10^{-10}$ to $10^{-12}$ $cm^2$, and the relaxation time $T_1 \approx 10^{-8}$ sec. Consequently, the saturation of the atomic level population takes place for an intensity of $I_{sat} \approx$ 0.1 to 10 watts/$cm^2$. For the forbidden transitions of the atoms, the cross section of the resonance interaction is much less, but then it increases the relaxation time $T_1$ correspondingly, so that the intensity of the saturation lies in the same band. For example, for the transition on the $R_1$ line of a ruby crystal the saturation comes for intensities of $I_{sat} \approx 10^3$ watts/$cm^2$, but, of course, the emission must act on the transition for a sufficient time at least for the time $t_{mutual} > T_1 \approx 10^{-3}$ sec (for a ruby).

For the effect of absorption saturation observed as transillumination of an absorbing medium for intense light is the first nonlinear optical effect observed before the creation of lasers. Academician S. I. Vavilov predicted the existence of nonlinear optical phenomena long before they entered into optics with the discovery of coherent light sources, and he persistently searched for them. Together with his students V. L. Levshin, in 1928 he succeeded in observing 2% transillumination of uranyl glass (glass with uranium ion admixture) on illumination with a powerful spark. The success of the experiment came from the anomalously large relaxation time $T_1$ in the uranyl glass (about $10^{-2}$ sec). Now the illumination effect is widely used in quantum electronics in the self illuminating shutters mentioned in Chapter 2. The absorption saturation corresponds to the transition to the excited state of a noticeable portion of the particles interacting with the light field. In this sense it is always presnt in numerous experiments with strongly excited atoms and molecules.

In the short light pulse field having a duration of $\tau_{pulse} < T_1$, a characteristic parameter of the nonlinearity is not the intensity, but the pulse

flux (in joules/cm$^2$). The energy flux which is sufficient for the saturation of the absorption is defined by the expression

$$\mathcal{E} \gtrsim \mathcal{E}_{\text{нас}} = \hbar\omega_0/\sigma_{\text{рез.}} \qquad (5.13)$$
(a) (b)

Key: a. sat b. res

For example, for the $R_1$ line of the ruby crystal $_{\text{sat}} \approx 6$ joules/cm$^2$.

Coherent Saturation. If the induced transition rate becomes comparable or exceeds the rate of establishment of random phase distribution of the wave functions resonance-interactining with the particle field, that is, the rate of dephasing of the elementary dipole elements induced by the resonance light field, then the nonlinear interaction of the field with the material becomes coherent. The coherent nonlinear effects occur for intensities satisfying the condition

$$I > I_{\text{кор нас}} = \hbar\omega_0/\sigma_{\text{рез}} T_2, \qquad (5.14)$$
(a)

Key: a. coh.sat

where $T_2$ is the characteristic phase relaxation time of elementary dipole elements. For condensed media the time $T_2$ is very small and depends on the temperature. For example, for the transition on the $R_1$ ruby line at room temperature $T_2 = 10^{-12}$ sec, and at the liquid nitrogen temperature $T_2 = 3.5 \cdot 10^{-10}$ sec. Therefore the coherent nonlinear effects in the condensed media at room temperature can be observed only for very high intensities (for ruby $I_{\text{coh.sat}} = 10^{12}$ watts/cm$^2$), where nonresonance destruction of the medium by a powerful light field takes place. However, at low (nitrogen and helium) temperatures they are entirely observable. In low pressure gases the interaction of the particles among each other is low; therefore the phase relaxation time increases to values of $T_2 \approx 10^{-8}$ sec at a gas pressure of 1 mm Hg and it increases proportionally with a decrease in pressure. The coherent phenomena can be observed for moderate intensities: 100 watts/cm$^2$ for atoms and $10^3$ to $10^5$ watts/cm$^2$ for molecules.

The coherent saturation of the absorption of the medium leads to a series of observable nonlinear optical effects. The clearest is the effect of self-induced transparency of the resonance-absorbing medium. This effect is manifested on transmission of powerful ultrashort pulses (with a duration of $\tau_{\text{pulse}} \ll T_2$) of light through the resonance-absorbing medium to complete this appearance of absorption. Physically it is explained by the fact that the photons of the front part of the pulse convert all of the absorpting particles to the excited state. The medium turns out to be in the inverted state and

begins stimulated emission, returning all of the energy absorbed from the pulse to it.

Nonlinearity of the Index of Refraction. As is known, the index of refraction of a medium is determined by the interaction of a light wave with external (optical) electrons of atoms. In a weak light field the oscillations of the electron charge surrounding the nucleus in the atoms or molecules follows the oscillations of the electric field intensity. The dipole moment induced in the optical medium on the field frequency depends linearly on the light field intensity (Figure 20,a). In other words, the index of refraction determining the propagation of the light wave in an optical medium does not depend on the light intensity where it is small. However, in a sufficiently powerful light field the amplitude of the oscillations of the electron cloud with respect to the nuclei does not follow proportionally after the intensity of the light field or, other words, it becomes a nonlinear function of the light field intensity (Figure 20,b, c).

The nonlinear response of the medium to a powerful light field consists, first of all, in variation of the index of refraction of the medium $n_0$ and, secondly, the appearance of higher harmonics in the polarizability of the optical medium. In media in which the symmetry of the shift of the electron charges in the light field is disturbed (for example, crystals without the center of symmetry or inversion), the harmonics of the light oscillations on the double light frequency $2\omega$ occur. Such media are called quadratically nonlinear. In symmetric media (gases, liquids, crystals with center of symmetry) the second and other even harmonics do not occur, but the third and other odd light harmonics appear. Such media are called medic with cubic nonlinearity.

Any transparent optical medium obviously will be sharply nonlinear if the intensity of the electric field of the light wave becomes comparable to the intensity of the intraatomic electric field defined by the expression (5.8), that is, where the light intensity reaches values of $10^{16}$ to $10^{17}$ watts/cm$^2$. In practice the nonlinear effects of the type of generation of the harmonics are manifested for much smaller intensities as a result of the accumulation of nonlinear distortions of the light field in a medium with propagation of the light wave. On the light path length in the medium L the nonlinear effects are manifested for intensities which are $L/\lambda$ times less, where $\lambda$ is the length of the light wave. Any optical medium in the light field with intensity $10^{12}$ to $10^{13}$ watts/cm$^2$ on the path L = 1 cm must generate optical harmonics. This is highly obvious from the experiments with a laser plasma in which under the effect of a powerful laser field, many new frequencies always arise as a result of the nonlinear effects. In practice this method of "gross force" in nonlinear optics is not used as a result of destruction of the median in such powerful light fields. At the present time, a number of so-called "nonlinear crystals" have been found and studied which have simultaneously very high nonlinearity and high optical improvement, which is important for accumulation of the nonlinear distortions along the entire path of the light wave in the crystal. The nonlinear crystals permit generation of the harmonics and mixing of the light waves of different frequencies for moderate radiation intensities (on the order of $10^7$ to $10^9$ watts/cm$^2$).

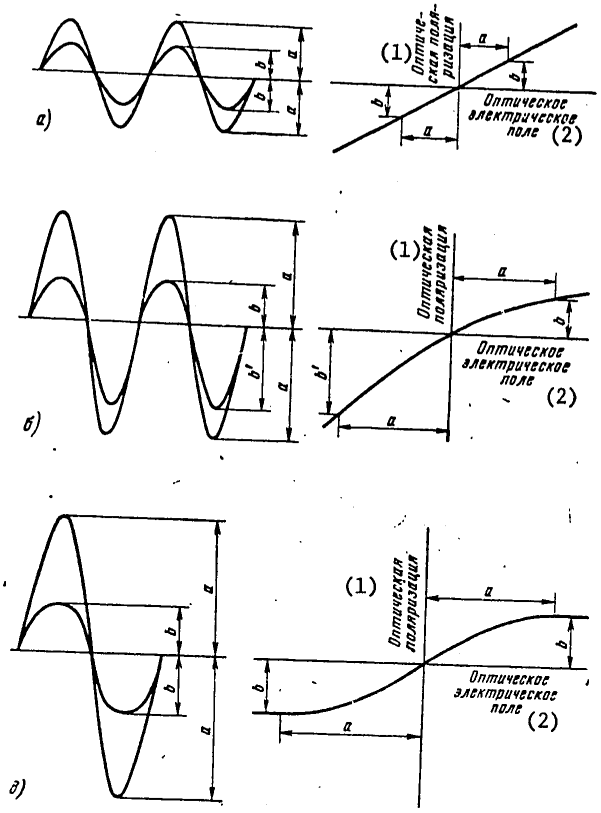


Figure 20. Explanation of the nonlinear behavior of an optical medium in a powerful light field responsible for the generation of optical harmonics: a -- in a linear medium the optical polarization is proportional to the intensity of the light field; b -- in a medium with quadratic nonlinearity in optical polarization, a second harmonic is generated; c -- in a medium with cubic nonlinearity in optical polarization under the effect of a strong field a third harmonic of the light wave appears.

Key: 1. optical polarization
2. optical electric field

The variation of the index of refraction in an intense light field leads to many of the most interesting phenomena for propagation, refraction and reflection of light which do not even have an analog in the physical optics of weak light intensities. Among them it is necessary to mention the phenomenon of self-focusing of light which has already been indicated as the cause of the

limitation of output power of powerful lasers. This phenomenon was predicted by Soviet scientist G. A. Askar'yan. As a resule of variation of the index of refraction proportionally to the local light intensity, transverse gradients of the index of refraction occur in the light beam. Therefore as a result of refraction, the light beam is deflected into the region with increased index of refraction, that is, it is focused on the light beam axis. This phenomenon occurs even in an entirely uniform optical medium, for the optical nonuniformity is created by the light beam itself. There are several different mechanisms of variation of the index of refraction in the strong light field: the Kerr effec, that is, orientation by the electric field of the light wave of anisotropically polarized molecules; electrostriction, that is, compression of the dielectric in the light field; the thermal effect as a result of radiation absorption in the medium, and so on. Each of these mechanisms have different inertia and is manifested differently in different media. Therefore the study of the self-focusing is one of the most complex divisions of nonlinear optics.

Multiphoton Ionization and Optical Breakdown. Simultaneous absorption by a particle (atom, molecule, ion, and so on) of several photons leading to particle ionization is possible in a strong light field. With respect to order of magnitude, the intensity required for multiquantum ionization of an atom is comparable to the intensity for which the intensity of the electric field of the light wave will become close to intraatomic. The experimenters encountered the processes of this type for the first time immediately after the development of the first ruby lasers with Q-factor modulation. When focusing the radiation pulse of such a laser in the air, the so-called "laser spark" occurred without using a constant electric field and external electrode. A quite powerful laser pulse can create an extended "laser spark" tens of meters long in the air. Such sparks can even be used to shape collimated high-voltage discharges.

The mechanism of the occurrence of the laser spark is comparatively simple and resembles ordinary electric discharge. The free electrons always available in the material or arising, for example, as a result of multiquantum ionization, gather energy in an intense light field and cause subsequent ionization of other particles on collisions with them. This process of interaction of electrons in a gas or condensed medium with a powerful light field has an avalanche nature and is called "otical breakdown" of the medium. The standard magnitude of the light field intensity for which optical breakdown takes place is $10^{10}$ watts/cm$^2$. In such light fields any material is converted to a plasma. Obtaining and heating a plasma under the effect of powerful laser radiation is perhaps the most interesting and important effect of nonlinear nonresonance interaction of a powerful light field with matter. This effect is the basis for the laser methods of realizing controllable thermonuclear fusion discussed in Chapter 6.

Generation of Electron-Positron Pairs. In conclusion let us consider the process which is possible only for exceptionally high intensities of the light field which can be considered as a type of limit for the possibilities of high energy intensity and density physics and engineering. We have in

mind the generation of "electron-positron" pairs in a powerful light field, that is, the phenomenon of the qualitative transition from high particle intensities with low energy (photons) to low particle intensities with high energy (electrons and positrons). Such a process is possible in a quite powerful electric field, and it is possible to make estimates of the required intensity as academician Ya. B. Zel'dovich demonstrated.

For generation of a pair of particles $e^+ + e^-$ it is necessary that the work of the electric field with respect to "separation" of opposite charges $e^+$ and $e^-$ by the distance of the De Broglie wavelength of the electron $\lambda = h/mc$, that is, the value of $eE\lambda$ was sufficient to compensate for the energy expenditures on generation of the $2mc^2$ pair. Hence, we immediately have the estimate for the critical electric field intensity:

$$\underset{\text{(a)}}{E_{\text{рожд пар}}} = 2m^2c^3/e\hbar = 3 \cdot 10^{16} \text{ volts/cm.} \qquad (5.15)$$

Key: a. pair generation

The energy density of such a light field $u_{cr} = 10^{19}$ joules/cm$^3$ and, consequently, in accordance with the principle of energy and mass equivalence, the mass density of such a field reaches values of $10^5$ g/cm$^3$, that is, it exceeds by $10^4$ times the density of the standard metal (!). Even for a light energy density $10^3$ times less than the critical value it would be entirely possible to record the generation of single pairs of $e^- + e^+$. Theretically this late energy density can be reached by focusing a light pulse with a power of $10^{17}$ watts on an area on the order of 0.2 microns in size. Such powers of the laser radiation are far beyond the length of the possibility of modern laser engineering. However, it is still impossible to consider such power levels theoretically inadmissible. On the contrary, the use of the effect of concentration of the light energy by focusing a coherent light field in empty space is highly theoretical. In any other methods, a powerful electric field is created on electrodes which, of course, give up their electrons much more easily than they are extracted from a vacuum.

## 5.3. Nonlinear Distortions and Correction of Powerful Light Beams

The nonlinear phenomena in an active amplifying medium of a laser, in transparent transmitting and reflecting elements of the laser essentially limit the limiting characteristics of the laser beams such as the intensity, the energy flux and the divergence. Above, in Chapter 2 we have briefly mentioned the main "scourge" of powerful pulse lasers -- self-focusing of powerful beams and methods of controlling it (apodizing irises and spatial filters). In a powerful light field of a laser the index of refraction of a transparent dielectric usually increases by the amount $\delta n_2 = 5 \cdot 10^{-7}$ cm$^2$/gigawatt with a radiation intensity of $10^9$ watts/cm$^2$. It is clear that on the path L the wave front in the center of the light beam with an intensity of one gigawatt/cm$^2$ lags by the amount $\delta L = \delta n_2 IL$ by comparison with the wave

front on the edges of the beam where the intensity is low. Thus, a plane wave front is converted to a converging spherical wave front, that is, the light beam is self-focused as a unit whole. The threshold of such self-focusing of the light beam is achieved where the nonlinear phase shift of the wave front $\Delta\Phi = 2\pi(\delta L/\lambda)$ becomes equal to $2\pi$, that is, $\delta L = \lambda$, at a distance equal to one Fresnel length of the light beam $L_\phi = a^2(2\pi/\lambda)$, where a is the light beam radius, $L_\phi$ is the distance at which the increase in beam diameter becomes noticeable as a result of its diffraction. The magnitude of the critical power $P_{cr} = \pi a^2 I_{cr}$, and it is defined by the simple expression

$$P_{\text{кр}}=\lambda^2/2\delta n_2. \qquad (5.16)$$
(a)

Key: a. cr

The standard value of $P_{cr}$ on a wavelength of $\lambda = 1$ micron for $\delta n_2 = 5\cdot10^{-7}$ $cm^2$/gigawatt is 10 megawatts. In the multistage lasers the power of the light beam reaches values which are $10^4$ to $10^5$ times larger than the standard value of the critical power. If special measures are not taken, then this powerful light beam quite rapidly decays as a result of nonlinear diffraction into individual beams, each of which is hit by a power on the order of the critical power, that is, self-focusing of the light beam takes place. In the powerful lasers, special elements are used, in particular, spatial filters (see Chapter 2), to eliminate this extremely undesirable phenomenon. The radical method of controlling self-focusing would be the development of optical materials with small values of $\delta n_2$ or compensation $\delta n_2$ as a result of introduction of a special component into the material having a negative value of $\delta n_2$.

All of the optical transparent materials have limited beam strength as a result of self-damage of them in powerful light fluxes. Two types of self-damage are clearly observed: on the surface of the materials and inside the volume of the materials. The study of the destruction of glass polished and coated with films demonstrated that the cause of self-damage is microinclusions on the surface remaining, for example, after polishing, that is, unavoidable "pollution" on the surface. The self-damaged threshold is almost identical for all optical materials and for radiation on $\lambda = 1.06$ microns it is in the range of 10 joules/$cm^2$. The damaged threshold for metal mirrors is in the range of 1 to 10 joules/$cm^2$, and it is maximal for mirrors treated directly with a diamond needle without polishing. The data on the volumetric self-damage of the materials are highly contradictory, for the mechanism of the phenomenon has still not been finally discovered. At the present time the point of view of volumetric destruction just as the result of optical breakdown in the dielectric, that is, the development of avalanche ionization in a powerful light field, is the most widespread. This conclusion was drawn on the basis of investigation of the self-damage threshold for variation of the wavelength and duration of the laser pulses. However, many experiments indicate that the actual destruction thresholds in a volume, just as on the

surface, obviously are determined by the light absorption on the microinclusions which leads to heating of the individual points in the dielectric.

Obviously, after careful study of the mechanism of volumetric self-damage to the dielectrics, it will be possible to proceed to the next step -- the development of special optical materials with increased radiation strength.

In order to eliminate the distortions of the wave front of light beams of powerful lasers occurring either in the lasers themselves or on passage of them through optical media, a turbulent atmosphere, and so on, methods of dynamic correlation of the wave front are developed. This new area of modern optics is sometimes called adaptive optics inasmuch as the parameters of the adaptive optical systems are somehow tuned to the distortion parameters of the light beams in order to compensate these distortions. Two possible approaches are being developed -- active adaptive optics and nonlinear adaptive optics.

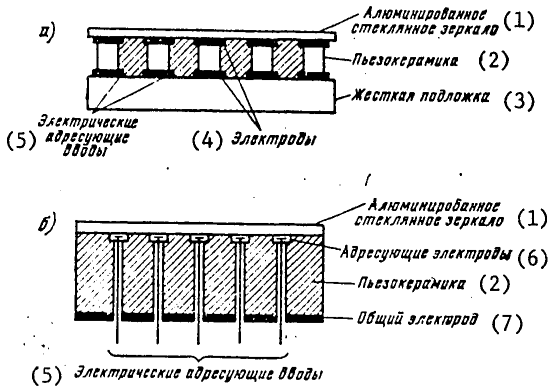


Figure 21. Two different structural designs of adaptive mirrors, the shape of the surface of which is controlled electrically using piezoelements.

Key:
1. aluminized glass mirror
2. piezoceramic
3. rigid substrate
4. electrodes
5. electrical addressing inputs
6. addressing electrodes
7. common electrode

The ideas of active optical systems which are capable of compensation for the distortions of images of the stars occurring as a result of turbulence in the atomsphere were born in the 1950's, but it is only now with the development of low-inertia active optical elements that these ideas have been implemented in real systems. Active mirrors have already been developed in which the correction is made using a set of piezoelements supporting the flexible mirror on a monolith. The height of each piezoelement is controlled

independently by an electric voltage (approximately 1 kv per micron of shift). The structural design of such active mirrors is depicted in Figure 21. Of course, for control of the adaptive mirror, the multielement system is needed which measures the distortions of the wave front of the light beam incident on the mirror, the computer for processing the data obtained, calculation of distortions of the wave front and the generation of data for the control of a set of piezoelements. Now the times of dynamic correction have been reached which are shorter than $10^{-3}$ sec. This is entirely sufficient fo compensation for the distortions of the light beam in the turbulent atmosphere, for the characteristic nonuniformitys in the atmosphere rarely vary faster than in a time of $10^{-2}$ sec.

The ideas of the nonlinear adaptive systems are based on self-compensation of the distortions of the wave front of an intense light beam in a nonlinear medium. This is theoretically possible, for example, for nonlinear reflection of the light beam with "inversion" of the sign of the wave front distortions. This phenomenon of inversion of the sign and compensation of the distortions of the wave front was detected for the first time by Soviet researchers. In this case, according to the accurate expression of academician R. V. Khokhlov the nonlinear medium is a "magic mirror which changes the sign of the time." Now many possible paths of nonlinear self-compensation of the distortions of laser beams have been proposed and demonstrated. At the last, Tenth International Conference on Quantum Electronics (June 1978, Atlanta, USA) this problem was the subject of about 10 reports. Therefore it is possible to state with certainty that nonlinear adaptive optics of coherent light beams are an important, prospective area of applied nonlinear optics.

## 6. HIGH-TEMPERATURE HEATING OF MATTER

Powerful laser emission has high brightness and in accordance with the simple relation (5.7) very high effective temperature. Hence, we have the possibility of heating matter with laser emission to high temperatures, to thermonuclear temperatures. The laws of thermodynamics forbid the transmission of the energy from a cold body to a hotter one without the performance of additional work, the magnitude of which exceeds the magnitude of the transmitted energy. Therefore sunlight even collected by as large optical systems as one might like cannot be used to heat matter to a temperature of more than 6000°, for the heated matter immediately begins to return the energy to the sun. The very high effective temperature of laser radiation guarantees the absence of this effect even for a target temperature of millions of degrees. The creation and heating of a high-temperature plasma by laser radiation is a new area occurring at the junction of quantum electronics and plasma physics. We shall very briefly consider two possible applications of high temperature laser heating of a plasma -- the realization of controlled thermonuclear fusion and the creation of a laser in the x-ray region at the transitions of highly ionized atoms.

### 6.1. Laser Controllable Thermonuclear Fusion

The possibility of controlled production of thermonuclear energy in the fusion reactions of light nuclei in a high-temperature plasma and thus obtaining a clean and in practice inexhaustible source of power, has been actively investigated by the physicists of many countries for a quarter of a century. In our country many ideas of controllable thermonuclear fusion have been born and are being successfully developed, the basis for which is the combustion of heavy hydrogen isotopes in a high temperature plasma made up of deuterium, tritium and electron nuclei. The nuclei can enter into contact and react under thermodynamic equilibrium conditions if their kinetic energy is sufficient to overcome the electrostatic repulsion. Therefore the fusion reaction rate in deuterium-tritium plasma increases with an increase in temperature and reaches optimal values in the range of 100 million degrees.

The key experiment for the proof of the realizability of thermonuclear fusion is combustion of a deuterium-tritium plasma which requires the least temperature. By combustion we mean the release of thermonuclear energy equal with respect to magnitude to the thermal energy introduced into the plasma. For

ignition of a deuterium-tritium plasma with a temperature of 60 million degrees it is necessary that the product of the plasma density n (the number of ions per $cm^3$) and the time of its existence (or confinement) $\tau$ be equal to

$$n\tau \geqslant 10^{14} \text{ sec/cm}^3. \qquad (6.1)$$

Thus, for the first time it is necessary to create a plasma with a temperature of no less than 60 million degrees and, secondly, to hold it for a sufficient time in the hot state. The confinement time depends on the plasma density. Of course, in reality in order to create an advantageous thermonuclear electric power plant the criteria look much more rigid than (6.1), for useful thermonuclear energy must exceed by many times not only the thermal energy invested in the plasma, but all of the energy expended on creation and confinement of the plasma. Nevertheless, the criterion (6.1) can be considered as an index of the closeness to the physical realization of thermonuclear fusion.

For the creation of a high-temperature plasma, in practice all energy sources are suitable which insure sufficiently high energy densities (see Table 1). The nuclear explosion is already being used for the realization of thermonuclear fusion in thermonuclear bombs. However, this thermonuclear process is of course an uncontrolled explosion process, just as the nuclear blast initiating it occurring as a result of fast energy separation in a chain reaction of fission of heavy nuclei. However, the scientists and engineers must control the occurrence of the chain nuclear reaction in the nuclear reactors. This has made it possible to develop many useful applications of nuclear power, in particular, to create nuclear power engineering. The next natural and logical step is to achieve control of the thermonuclear reaction. However, this step turned out to be the most difficult in modern physics and engineering. For the last 25 years highly significant efforts have been undertaken for the ignition of a deuterium-tritium mixture in practice by all admissible sources of high energy density: a powerful pulse electric discharge focused by a powerful laser beam, a high-current electron beam. The possibilities of these sources encompass an enormous range of plasma densities: from $n = 10^{14}$ to $10^{15}$ $cm^{-3}$ for the creation and heating of a plasma by a powerful electric discharge to $n \gtrsim 10^{22}$ $cm^{-3}$ when heating the plasma with very powerful laser or electron beams. In accordance with the criterion (6.1) different sources with high energy density require entirely different confinement times.

In a plasma of comparatively low density ($n = 10^{14}$ to $10^{15}$ $cm^{-3}$) with a temperature of about 50 to 60 million degrees, confinement times on the order of several seconds are required. Obviously for this purpose good thermal insulation of the plasma and confinement of it from dispersion are required. This is now achieved by using special configurations of a magnetic field (magnetic confinement). The most prospective system of this type is made up of the "Tokamak" devices developed at the Nuclear Power Institute imeni I.V. Kurchatov under the direction of academician L. A. Artsimovich. The plasma density with a temperature of 50 million degrees reaches values of $10^{15}$ $cm^{-3}$,

and the confinement time, a fraction of a second. Neutrons are observed under these conditions which occur during the course of the fusion reactions. Let us emphasize that in the Tokamaks, the heating of the plasma to thermonuclear temperatures and confinement of the plasma are realized directly using an electric current in the plasma itself and in the magnetic traps surrounding it.

The pulse sources with high energy density (laser and electron beams) create a much denser plasma, but for a comparatively short time on the order of $10^{-8}$ to $10^{-9}$ seconds. It is possible either to get away from the confinement of such a dense plasma in general (the so-called inertial confinement mode where the time of thermonuclear combustion turns out to be less than the plasma dispersion time) or even to use the most powerful photon or electron beams for additional compression of the plasma. The pulse methods of realizing controlled thermonuclear fusion have been developed to a lessor degree, but, in the opinion of many scientists, they are entirely competitive with the stationary method used in the Tokamaks. The heating and confinement of a high temperature plasma by photon beams somewhat raise the requirement on the thermonuclear yield, inasmuch as the efficiency of the conversion of electric power to the power of a high-coherent laser beam in powerful lasers is very small (1-10% in the best case, see Chapter 2). It is true that for a fast electron beam the conversion efficiency is appreciably higher (to 50%), which is considered as a definite advantage of this method for the modern state of powerful laser equipment, in spite of the large difficulties of focusing it by comparison with the laser beams.

The possibility of heating the material to thermonuclear temperatures using laser radiation focused on the targed was theoretically substantiated by academician N. G. Basov and professor O. N. Krokhin in 1962 immediately after the creation of the first pulse lasers with Q-factor modulation (see Figure 2).

Their papers marked the beginning of the studies of laser controlled thermonuclear fusion (LUTS) successfully developed at the Physics Institute imeni P. N. Lebedev of the USSR Academy of Sciences and at a number of laboratories of the United States, France, the Federal Republic of Germany, England and Japan. In the laboratory of academician N. G. Basov by using the multistage neodymium glass amplifier in 1968 the emission of neutrons from a laser plasma was recorded. This important result, which opens up the road to numerous experiments with high temperature heating of the material by laser emission was reproduced in the laboratories of the United States and France. The properties of the neutrons emitted by the laser plasma were carefully studied and conditions were found under which they have a thermonuclear origin.

However, the program of laser controlled thermonuclear fusion still was not considered as sufficiently competitive until at the beginning of the 1970's new possible technical solutions were published in the United States and the USSR, which lowered by several orders the requirements on the critical minimum energy of the laser pulse, that is, the energy beginning with which the energy released in the thermonuclear reactions exceeds the light energy

invested in the plasma. The physical meaning of the proposal consists in the possibility of obtaining superhigh compressions of matter with special laser irradiation of a spherical target of special design having defined dependence on time. This compression regime is called adiabatic. In understandable language this means that the laser pulse of defined shape compresses matter quite slowly so that shock waves will not occur to prevent compression. The idea of obtaining superhigh compressions of the heated high temperature plasma using comprehensive laser irradiation of the target was a longical continuation of the idea of using lasers for heating matter to thermonuclear temperatures. Since the thermonuclear reaction rate depends not only on the temperature but also the density of the plasma, an increase in density of the material by 10,000 times lowers by approximately the same number of times the requirements on the critical energy of the laser pulse. Here the fact turns out to be significant that for compression of the target by 10,000 times with respect to its normal density only 1% of the energy is required which is needed for heating the target to the ignition temperature.

Thus, the modern concept of laser controlled thermonuclear fusion is a combination of several successive steps in increasing the energy density which are provisionally depicted in Figure 22. The laser multistage amplifier (see Chapter 2) concentrates the energy in space and time from the intensity level of $10^5$ (intensity of the flash tube) to $10^{10}$ watts/cm$^2$ (laser beam intensity). The focusing of the laser beam provides for an increase in the energy flux by $10^4$ to $10^5$ more times. The presence of many parallel channels in a laser increases simultaneous comprehensive irradiation of a spherical target with a laser energy flux on the surface of $10^{14}$ to $10^{15}$ watts/cm$^2$ (see Figure 7). The hot gas around the target acts like a thermal lens, additionally focusing the light energy on the still smaller surface of the evaporated high-temperature bunch of material. As a result of this effect the light energy density reaches values of $10^{15}$ to $10^{16}$ watts/cm$^2$. The evaporation of matter from the surface causes recoil which continues to compress the target. The adiabatic compression (implosion) can be considered as equivalent hydrodynamic focusing concentrating the kinetic energy in a superdense bunch of material. This kinetic energy is converted to internal energy, that is, to the heating of superdense matter much faster than compression occurs. As a result of this last stage, energy fluxes of about $10^{19}$ watts/cm$^2$ can be reached for compression of the matter by $10^4$ times with respect to the normal density of the target.

The first successful experiments have been performed with respect to observation of the compression of the matter with comprehensive irradiation by a powerful laser emission. In these experiments powerful multichannel and multistage neodymium glass lasers described in Chapter 2 were used. The results were obtained which confirm the prospectiveness of using the laser method of heating the plasma to realize controlled thermonuclear fusion. In particular, the temperatures and densities of the laser plasma have been measured in a wide range of laser radiation fluxes; the mechanisms of nonlinear absorption and reflection of light have been discovered, neutron radiation fluxes (approximately $10^9$ neutrons per pulse) have been measured, and the thermal mechanism of their occurrence has been proved. Moreover, for spherical irradiation of

the target in the laboratory of academician N. G. Basov at the Physics Institute of the USSR Academy of Sciences secondary neutrons were recorded in a deuterium plasma which indicate the presence of a compressed nucleus with a density of 30 g/cm$^3$. In these experiments high (about $10^3$ times) volumetric compression of the shell (empty) targets, which are at the present time considered as the most prospective type of thermonuclear targets, was observed.

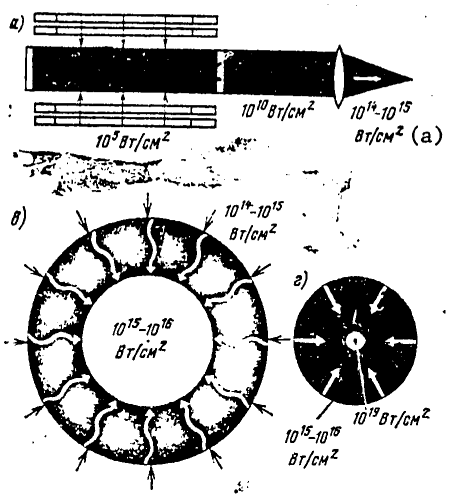


Figure 22. Stages of successive growth of energy flux density in laser thermonuclear fusion in the case of comprehensive irradiation of a spherical target on the devices shown in Figures 6 and 7: a--light energy concentration of flash tubes in time and space as a result of stimulated laser emissions; b--focusing of space-coherent laser beam; c--focusing of a spherical wave front in the target atmosphere; d--hydrodynamic focusing of energy in a compressible target.

Key: a. watts/cm$^2$

The critical energy of the laser radiation pulse is according to various calculations in the range of $10^5$ joules. With respect to optimistic estimates for such an energy level of the laser pulse it will be possible to realize such conditions experimentally in a superdense thermonuclear plasma which insure a quite large coefficient of thermonuclear boosting of the energy, that is, a significant excess of energy released as a result of the nuclear reactions in the heated volume of the plasma over the laser emission energy expended on heating it. None of the existing powerful lasers provides for the possibility of such experiments. However, the devices built in the USSR (Physics Institute of the USSR Academy of Sciences) and the United States (the Lawrence Livermore and Los Alamos Laboratories) with an output pulse

energy of $10^4$ joules will permit quite reliable prediction of how close this critical limit is and, consequently, the arrival at the next most important step of laser controlled thermonuclear fusion — the creation of an experimental pulse thermonuclear reactor using heating and compression of a hot material by the laser emission. Obviously, only after the development of powerful pulse lasers with an efficiency of about 10 to 20% will the theoretical possibility be opened up for the creation of an experimental-industrial thermonuclear electric power plant. The carbon dioxide power plant is still the best laser system from this point of view.

The experiments recently performed at the Los Alamos Laboratory in the United States with respect to spherical irradiation of the targets with nanosecond pulses of a $CO_2$-laser with an energy of several kilojoules demonstrated that an increase in the wavelength by 10 times by comparison with a neodymium glass laser did not lead to a noticeable reduction in the heating efficiency in spite of the expected poor penetration of the infrared radiation into the plasma. This appears to be highly theoretical for the creation of devices for critical experimentation, for only the $CO_2$-laser can be considered as a system for generating short pulses with an energy of $10^5$ joules. In addition, the $CO_2$-laser can operate in the frequency mode and, consequently, can be the basis for an experimental pulse thermonuclear reactor. Of course, the reactor based on a laser control thermonuclear fusion must prove its competitiveness with respect to other types of energy devices: operating reactors -- fast neutron breeders and designed thermonuclear reactors with magnetic confinement of the plasma. The final criterion determining the expediency and the time for the creation of one type of power reactor or another will be the cost of the electric power produced by it.

In the opinion of the American scientists responsible for the work program in the field of laser controlled thermonuclear fusion, the closest prospects for the use of laser thermonuclear fusion can be not the electric power plant, but a laser thermonuclear space engine. A jet engine based on a laser thermonuclear fusion can have characteristics which are inadmissible not only for the chemical fuel engines, but also plasma engines based on nuclear fission reactors. The total cost and the expenditures of labor on the creation of such a unique rocket engine operating on microexplosions of laser thermonuclear fusion are estimated at 1 billion dollars and 10,000 man-years. This is commensurate with the expenditures on the "Apollo" flights to the Moon, which does not exclude the creation of such systems before the end of the 20th century.

6.2. Problem of X-ray Laser

The possibility of creating a high-temperature plasma with high concentration of multicharge ions in very short times ($10^{-9}$ to $10^{-11}$ seconds) is opening up the prospects for the development of lasers on the junctions of highly ionized ions in the spectral range of 10 to 100 amps, that is, in the soft x-ray range. The highly ionized atoms are the most appropriate candidate for use as the amplifying medium of an x-ray laser for many reasons. In particular, as a result of strong photoelectric absorption any material in the

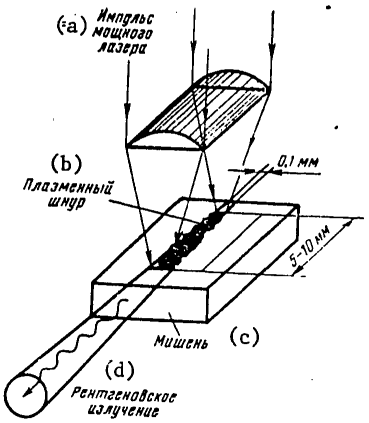


Figure 23. Possible diagram of an x-ray laser on the transitions of multidischarge ions in a column of high-temperature plasma when focusing a powerful laser pulse on the target by a cylindrical lens.

Key: a. powerful laser pulse
b. plasma column
c. target
d. x-radiation

ordinary state has extraordinarily low transparency in the entire x-ray range. However, the high-temperature plasma, the atoms of which have lost all weakly bound electrons is transparent for x-radiation with the exception of narrow spectral absorption lines on the quantum transitions of the electrons tightly bound to the ions.

When creating an inverse population of levels of the highly ionized atom, some of these narrow absorption lines can be converted to narrow amplification lines as is done in the existing gas lasers based on a low-temperature plasma. It is true that the very short lifetime of the excited states of the multiple discharge ions ($10^{-10}$ to $10^{-13}$ sec) and the high transition energies of the x-ray regions of the spectrum require very high pumping power of the plasma to obtain inversion even for a short time. The lifetime for the permissible x-ray transmissions is on the order of $\tau_{rel} = 10^{-15} \lambda^2$ sec, where $\lambda$ is the wavelength in angstroms. Consequently, the quantum transition with an energy of 1 kev ($\lambda$ = 12 Å) has a radiation lifetime of $10^{-13}$ sec. Estimates show that for pumping the x-ray laser in the region of $\lambda$ = 10 to 100 Å, powerful lasers are required ($10^{11}$ to $10^{12}$ watts), the emission of which must be focused on the target by a cylindrical lens in order to create an extended amplifying medium (see Figure 23). The high-temperature plasma column created in this way begins to disperse in the transverse direction into a vacuum or gas, passing successively through the entire range of densities, temperatures, and so on. It appears highly probable that at each point in time

the nonequilibrium state of the plasma will promote the occurrence of an inversion on the ion transitions and amplification of the radiation along the column.

Naturally the duration of the laser pulse must be quite small in order to create a high-temperature plasma in a strongly nonequilibrium state where the occurrence of an inversion and amplification on the transmission between any pair of levels are entirely possible. Approximately such laser pulses are generated on the powerful devices designed for investigation of laser thermonuclear fusion. Therefore it will be possible to create the x-ray lasers as a side result of the laser thermonuclear research.

The efforts to build an x-ray laser based on a laser nonequilibrium plasma have been made at many of the laboratories of the United States, the USSR and France. Several clear intensity anomalies have been observed in the emission along and across the "column" of the laser plasma on certain lines in the range of 60 to 600 Å. However, obviously only after obtaining the x-ray pulse at least with geometric intensity determined by the ratio of the diameter of the amplifying medium to its length, it will be possible to talk with certainty about the progress in this important, theoretical area of quantum electronics.

## 7. SELECTIVE EFFECT OF LASER EMISSION

By the selective effect of laser emission on a material we mean the effect of light on the atoms or molecules of a defined variety (for example, a defined isotope) in the mixture of in individual cases on defined bonds in a complex molecule. For the selective effect of the radiation on matter the following are required: high monochromaticity of the stimulating radiation with a sufficient power level on the given wavelength; selectivity of the elementary process of the interaction of the radiation with matter (the existence of narrow absorption lines); maintenance of the selectivity obtained with subsequent physical and chemical processes.

The first condition is very difficult to satisfy using ordinary light sources. Only on defined, very few wavelengths is it possible to obtain sufficiently intense narrow spontaneous radiation lines. The creation of the laser sources of coherent light with tunable wavelength of the emission has opened up the possibility of selective excitation of in practice any quantum states of the atoms and molecules with excitation energy of 0.1 to 10 ev. In the entire range of wavelengths from 2000 Å to 20 microns it is now possible to obtain coherent radiation with power sufficient for the saturation of the quantum transition, that is, the excitation of a significant portion of the atoms and molecules to the required quantum state. It is this qualitatively growing level of quantum electronics that has made it possible in 1969 to 1970 to begin the systematic studies of the selective effect by laser emission on matter.

At the present time, as a result of the basic research performed primarily at the institute of spectroscopy of the USSR Academy of Sciences, basic prospective methods of selective effect by laser light on matter have been found and studied which are based on multistep and multiphoton processes of excitation, ionization and dissociation of atoms and molecules. The most prospective processes have been successfully tested on the experimental devices for laser separation of isotopes, and they are being introduced in industry. The first successful experiments are being performed with respect to laser selective purification of the impurities used in semiconductor technology.

### 7.1. Methods of Laser Separation of Isotopes

One of the most important and primary problems in a area of the selective effect by laser light on matter is unconditionally the laser separation of

isotopes. An exceptionally important role in nuclear engineering and power engineering in materials with isotopic composition distinguished from the natural composition and signficant deficiencies of all of the existing methods of separation of isotopes, on the one hand, and the theoretical possibility of developing new laser methods, on the other hand, are forcing a persistent search for new ways to solve the problem of separation of isotopes. The possibility of the selective effect on the isotopes by the laser emission has opened up a very attractive field of activity for scientists and engineers striving to solve this problem. The use of the latest data on the structure of atoms and molecules and their interaction with coherent laser emission, the latest achievements in the field of tunable lasers with a clear practical goal -- finding and developing new methods of separating isotopes which will be cheaper, more productive, more flexible, less energy consuming, and so on in the existing methods -- are combined. There are hundreds of scientists at tens of laboratories of a number of countries that are now working in this urgent area.

For the separation of isotopes it is possible to use the well-known phenomenon of an increase in reactivity of atoms and molecules on absorption of a photon, that is, on photoexcitation. All of the methods based on the chemical reactions of excited particles are called photochemical. On the other hand, the selectively excited atoms and molecules have less ionization and association energy than the unexcited ones and, consequently, can be ionized or dissociated by additional laser emission. This photophysical approach to the selective effect of light on matter has been proposed and was successfully developed at the Institute of Spectroscopy of the USSR Academy of Sciences. The photophysical approach in the separation of isotopes differs significantly from the previously known photochemical approach.

Let us consider an atom having the ground and excited energy states and also the continuum of states corresponding to separation of the external electron from the atom, that is, ionization of an atom (Figure 24,a). The atoms of the selected isotope can be excited by monochromatic radiation, for the atoms of another isotope have somewhat shifted energy levels. In 1935 successful experiments were performed in Germany with respect to the optical photochemical separation of mercury isotopes based on a selective increase in the reaction rate of certain mercury isotopes with oxygen on excitation of them. However, the experiment with mercury atoms is exceptional as a result of the presence in them of metastable triplet states. Progress in the experiment has also been promoted by the use of intense mercury lamps emitting in contrast to the ordinary incandescent lamps, comparatively intense radiation in narrow spectral lines, on the mercury atom absorption wave lengths. Therefore the photochemical approach could not be widely applied to the other elements even when using laser emission.

The photophysical approach based on the capacity of intense laser emission to convert a significant part of the atoms to any given excited state which can be realized only by using laser emission is much more universal and flexible. The photoionization of the selectively excited atoms by additional laser emission until they return to the ground state or transfer their excition

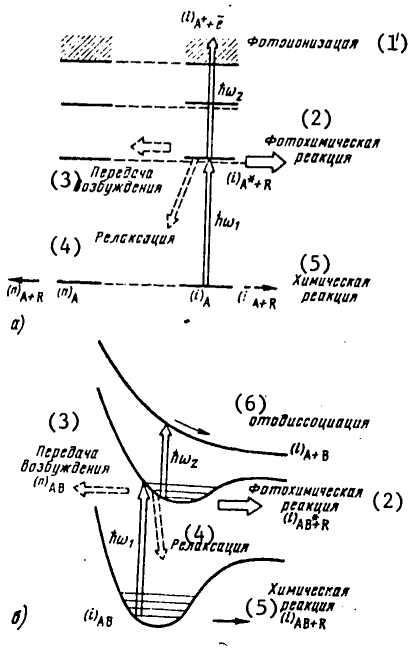


Figure 24. Universal processes of the two-stage selective effect of laser emission on atoms and molecules and comparison of them with photochemical processes: a -- selective, two-step photoionization of atoms; b -- selective, two-step photodissociation of molecules.

Key:
1. photoionization
2. photochemical reaction
3. transmission of excitation
4. relaxation
5. chemical reaction
6. photodissociation

on collision with atoms of another isotopic composition, is realized in this approach. This is theoretically always possible with sufficient intensity of the ionizing radiation, for the probability of photoionization is proportional to the intensity of the additional radiation. Thus, the selective photoionization, in contrast to the photochemical reaction, does not require collisions of the excited particles with other particles and, consequently, is entirely controlled by laser emission.

An analogous situation is also possible for molecules (Figure 24,b). With the photochemical approach the selectively excited molecule on collision with another particle (acceptor R) must enter into chemical reaction with a rate exceeding the reaction rate for the unexcited molecules. The processes of relaxation of excitation and mixing of excitation during collisions of the

molecules of different isotopic composition compete with the photochemical reaction process. These difficulties are eliminated on photodissociation of selectively excited molecules with the possibility of additional laser emission with a rate exceeding the rate of all the harmful competing processes with subsequent chemical binding of the radicals formed. This approach permits complete control of the selective effect of the laser radiation on the molecules of defined isotopic composition.

The first successful experiment with respect to the selective two-stage photoionization of atoms (in the example of rubidium atoms) was performed in 1971 at the Spectroscopy Institute of the USSR Academy of Sciences by R. V. Ambartsumyan, V. S. Letokhov, et al., and in 1972 the isotopically selective two-stage photodissociation on molecules was realized for the first time there (in the example of ammonia molecules and nitrogen isotopes). In the same years the Institute of Spectroscopy of the USSR Academy of Sciences was, so far as we know, the only one in the world where systematic work was done in this field. Since that time the situation has changed significantly. The methods developed at the Spectroscopy Institute were used to separate the isotopes first in indicator amounts under laboratory conditions and then in gravimetric amounts -- for the first time in the USSR and the United States. Now the laser separation of isotopes is recognized as one of the highly effective applications of coherent light. The development of these methods must significantly reduce the cost of enrichment of the majority of isotopes required in science and engineering in limited quantity and also, what is entirely possible, the isotopes required in the atomic industry on a large scale. However, far from all of the laser methods used in the laboratories for separation of isotopes in indicator or even in gravimetric amounts, are prospective for separation of isotopes on an industrial scale. The method potentially suitable for industrial use must first provide for the possibility of generation of laser emission with an average power level from 1 kilowatt to 1 megawatt (depending on the required output capacity); secondly, the laser must be sufficiently economical and simple to manufacture and maintain. These requirements greatly limit the number of methods usuable on an industrial scale with lasers known to the present time. In practice obviously there is still a unique method satisfying the formulated requirements. It is based on the use of the phenomenon of isotopically selective dissociation of multiatomic molecules by powerful infrared radiation pulses of a $CO_2$-laser discovered at the Spectroscopy Institute of the USSR Academy of Sciences in 1974. After 6 months this method was reproduced at Los Alamos in the United States and now is investigated in tens of laboratories of the entire world. For practical realization of this method it is most significant that it uses the radiation of the simpler and cheaper $CO_2$-laser which has standard efficiency of 5-10%, and its average power now reaches on the order of 1 kilowatt or more (see Chapter 4).

The representation of the standard experiment with respect to laser enrichment by powerful infrared radiation is presented by Figures 25 and 26. The pulse $CO_2$:$N_2$:He laser with transverse discharge only emits a few joules per pulse with a duration of 100 nanoseconds, that is, it has a power of several tens of megawatts. The wavelength of the emission is tuned to the region of

9-11 microns by rotating the diffraction grating which serves as a frequency-selective mirror which for generation selects the required rotational-vibrational lines of the $CO_2$ molecules. Part of the radiation is removed by the diffraction grating from the resonator, and it is concentrated with the help of a long-focus lens in a couvette. In the caustic region the intensity of the focused radiation reaches from hundreds to thousands of megawatts per square centimeter.

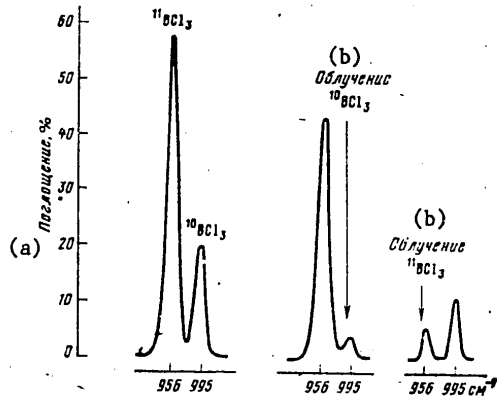


Figure 25. Infrared spectra of $BCl_3$ molecules in a couvette before and after irradiation of each of the isotopic molecules having the effect of separation of the $^{10}B$ as $^{11}B$ isotopes.

Key: a. absorption, %
b. irradiation

Molecular gas at low pressure -- on the order of 1 mm Hg is admitted to the reactor. Molecules are selected which have vibrational bands in the frequency tuning range of the $CO_2$-laser. There are very many such molecules ($BCl_3$, $SF_6$, $SiF_4$, $OsO_4$, $CF_3I$, $CH_3CN$ and tens of others). During the course of each pulse, several percentages of molecules dissociate in the reactor in the vicinity of the strong field. If the volume of the strong field region is much less than the total volume of the reactor, then for dissociation of a noticeable proportion of the molecules the reactor must be irradiated a multiple number of times. If the dissociation products recombine with the formation of an initial molecule, acceptor molecules are added to the reactor which provide for chemical binding of the radicals formed. The isotopic and chemical composition of the stable initial and final products are analyzed on a mass spectrometer and by the infrared spectra.

Figure 25 shows the results of an experiment performed at the Institute of Spectroscopy of the USSR Academy of Sciences in 1974 in which dissociation of $BCl_3$ molecules was realized. A mixture of $BCl_3$:$O_2$ was irradiated where the oxygen serves as the acceptor of the boron atoms torn off the $BCl_3$ molecules

or it picks up the boron atom from the highly excited $BCl_3$ molecule. As a result of these processes, first the BO radical is formed, and then the $B_2O_3$ molecules which precipitate on the wall of the couvette. On the left in Figure 25 we have the infrared spectrum of the $BCl_3$ molecule of natural isotopic composition before irradiation. The large isotopic shift existing in the oscillatory spectrum of this molecule permits selective excitation and dissociation of the molecule with the required boron isotope. If the laser frequently is tuned to the absorption band of $^{10}BCl_3$, then on irradiation in a residual gas, the concentration of the corresponding boron trichloride molecules decreases. When tuning the laser frequency to the absorption band of $^{11}BCl_3$, the $^{11}BCl_3$ concentration decreases.

Analogous results were also obtained for many isotopes in tens of other multiatomic molecules. For example on dissociation of the $SF_6$ molecule, enrichment of the gas mixture with S-34 and S-36 isotopes is achieved. The coefficients of enrichment of the residual gas reach several thousands. With an intensity of the radiation of 200 Mwatts/cm$^2$, approximately 12 ev are expended on dissociation of one $SF_6$ molecule. The energy expenditures exceed the dissociation energy of the molecule (about 4 ev for $SF_6$), for part of the excited molecules absorb many photons, but they do not reach the dissociation boundary. Nevertheless, for a laser efficiency of 10%, this value corresponds to highly moderate expenditures of electric power -- on the order of 120 ev on the release of 1 atom of the selected isotope.

The simplicity and technological nature of the described method of laser separation of isotopes has made it possible in the shortest possible time to begin introduction of it into industry. At the Nuclear Power Institute imeni I. V. Kurchatov, jointly with the Spectroscopy Institute of the USSR Academy of Sciences, an experimental device is being built for the study of the process of isotope separation using a pulse-periodic $CO_2$-laser with an average power to 1 kilowatt. This type of laser was already investigated in Chapter 4. Figure 26 shows the simplified diagram of this experimental device. The emission of the laser is directed into a light guide couvette with walls that reflect the infrared radiation well, which insures high intensity over the entire length of the couvette. In one irradiation pulse up to 20% of the $SF_6$ molecules dissociate. Inasmuch as the laser operates with high pulse repetition frequency (to 200 hertz), the strongly enriched mixture, after several laser pulses, is removed from the couvette by fast pumping of it through openings in the walls of the light guide couvette.

In the enriched gas mixture approximately 50 watts of laser radiation were absorbed. Under these conditions, an output capacity of the device of about 6 g/hr of S-32 isotope with 99.5% enrichment (natural S-32 content 95%) and about 0.3 g/hr of S-34 isotope with 50% enrighment (natural content 4%) was achieved. The output capacity of this first experimental device was limited by the small radiation absorption coefficient in the operating couvette (about 10%). At the present time systems have been developed with selective dissociation of the molecules under the effect of two laser emission pulses

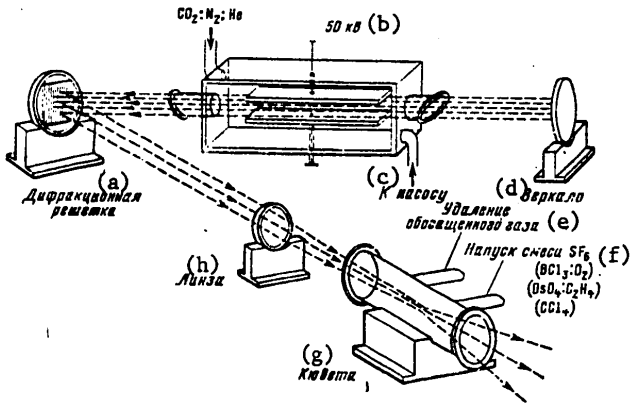


Figure 26. Simplified diagram of an experimental device for laser separation of sulfur isotopes by the method of dissociation of the $SF_6$ molecules by emission of a pulse-periodic $CO_2$-laser with an average power of 1 kilowatt depicted in Figure 17. The irradiated mixture ($SF_6$ + the acceptor molecule $H_2$) is rapidly pumped through the light guide couvette. At the top is a simplified illustration of the excitation of the vibrational levels of one of the isotopic molecules up to the dissociation energy in a strong infrared field.

Key:
a. diffraction grating
b. 50 kilovolts
c. to the pump
d. mirror
e. removal of enriched gas
f. admission of the $SF_6$ mixture
g. couvette
h. lens

with different wavelengths in the vibrational absorption band region. Such systems insure high selectivity of the dissociation with moderate level of radiation intensity ($10^5$ to $10^7$ watts/cm$^2$) and absorption of the radiation on comparatively short length (several meters) of chemical reactor.

7.2. Economics and Engineering of Laser Isotope Separation

From the point of view of economics the most important application of laser separation of isotopes is enrichment of the uranium with a U-235 isotope in order to obtain electric power in nuclear reactors. The world requirements for fuel for nuclear reactors from the present time to the year 2000 is estimated at approximately 6 million tons of $U_3O_8$. The cost of enrichment after processing this amount of ore is estimated at approximately 150 billion US dollars. The increase in effectiveness of the enrichment process using laser methods can significantly lower the cost. For heavy-water nuclear reactors enormous quantities of $D_2O$ are required. The current world output capacity which amounts to about 1000 tons/year is obviously inadequate. The economic importance of separation of the isotopes for the elements consists not in the demand for them at the present time, but the possibility of new applications of them in science, engineering, medicine, agriculture. These

applications will be developed only when the isotopes become available in large quantity and at low price.

The economics and the industrial scale of laser separation of uranium isotopes have still not been investigated sufficiently carefully, for no one method has been finally selected or is being finally realized in the experimental industrial devices. Considering the essence of this problem, it is necessary to remember that the cost of enrichment today is approximately 6% of the total cost of obtaining nuclear power. The sum of 150 billion dollars expended in 25 years is not so large by comparison with the recent increase in world price of oil by 100 billion dollars a year. Nevertheless, the researchers, designers and producers have reached the conclusion to convert some of the technically unjustifiable scientific ideas which were mentioned above into practical methods beginning with the scales of experimental plans to industry with multibillion dollar cost. Progress is not obvious here. The volume of nuclear industrial production in the United States can be illustrated by several figures. The standard reactor operating on light water generates $10^9$ watts of electric power. This requires the processing of 600 tons of $U_3O_8$ ore for the first fueling and then 200 tons annually for refueling. The fuel is enriched to 3% U-235 with a natural content of 0.75%. After enrichment the combined $UF_6$ uranium hexafluoride remains with 0.2 to 0.3% U-235 content. The enrichment is carried out at enormous gas diffusion plants. One such plant processes about 20,000 tons of $UF_6$ annually, consuming $2.4 \cdot 10^9$ watts of electric power. The cost of building the plant will be about 2.5 billion dollars, and the cost of the electric power plant for it, about 1.5 billion dollars. At the present time the United States foresees the necessity of putting a new plant of such a scale into operation every 1.5 years beginning in 1984. The same plant will be built in France. Some countries are improving the technology of the gas centrifuge method which can reduce the enrichment cost by 10-30%.

The potential possibilities of the laser processes used to reduce the enrichment cost can be illustrated by the fact that the gas diffusion requires 5 Mev, and the centrifuging method about 0.3 Mev of electric power for the separation of each U-235 atom. The total cost of enrichment will be 5 million dollars per ton of U-235.

For the laser process making use of selective ionization or dissociation, [illegible] energy of less 10 ev per atom or 0.1 to 10 kev of electric power would be required with a standard laser efficiency (from 10 to 0.1%). The chemical processing of the ore only for evaporation of solid material requires approximately the same amount of energy (5-10 ev divided by the natural content of U-235 equal to 0.0075). The cost of the electric power when using lasers with an efficiency of 1 to 10% will be negligibly small. Very high selectivity or enrichment factor characteristic of the majority of methods of laser separation of isotopes leads probably to a strong reduction in the amount of U-235 isotope left in the uranium, which must reduce the requirements for new ore to 40%. However, in order to obtain high output capacity (1000 tons of U-235 per year), it is necessary to create a large number of lasers with a total average power of $10^8$ watts of light

energy. With a laser efficiency of 10% from 0.1% to 1% of the energy produced by the nuclear power plants which operate on the obtained enriched nuclear fuel must be consumed to supply the laser enrichment devices.

At the present time it is still not clear which of the methods of laser separation of uranium isotopes will be the least expensive. The infrared photophysical method requiring the use of only one effective and already developed infrared laser would be the cheapest. It is clear that the method of two-stage selective ionization can be used to enrich uranium, but the cost of creating such a system and introducing it into industrial production would be very high. Obviously, prolonged research and development of a number of existing methods are required, before it will be possible to select the best.

Reducing the cost of the production of heavy water has exceptionally important significance. At the present time the cost of heavy water is about 25% of the cost of the heavy water reactor (100 million dollars for 100 tons of $D_2O$). If the cost of enrichment of deuterium were lowered by several times, then it would be economically advantageous to construct reactors using natural, unenriched uranium and heavy water. Theoretically this is entirely poossible, for in order to dissociate the HDO molecule in natural water a total of 5 ev are required. However, the low deuterium content (1 atom of D per 5000 atoms of H) requires the development of a method with selectivity of dissociation of the HDO molecules in the mixture with $H_2O$ of more than $10^3$. In this case alone will the light water molecules not be involved in the dissociation process. In the opposite case the energy expenditures will be inadmissibly large as a result of consumption of light power for the dissociation of light water. The multistage selective excitation of the HDO molecules in the multifrequency infrared laser field to the dissociation boundary undoubtedly is of interest for the solution of this problem.

Now there is no doubt of the economic advantageousness of the laser separation of various stable isotopes used in science and engineering in relatively small amounts ($^{13}C$, $^{17}O$, $^{18}O$, $^{40}K$, $^{48}Ca$, $^{57}Fe$, $^{79}Br$, $^{192}Os$, and so on). For the production of these isotopes at the present time the methods of fractional distillation or chemical exchange (light isotopes) and the electromagnetic method (isotopes of medium and heavy elements) are used, which are much less effective than the methods used to separate uranium and hydrogen. For laser separation of the isotopes, the lower cost limit is determined by the laser energy cost. If the total effectiveness of conversion of electric power to laser emission and then to enriched product is $10^{-3}$, then the price of the electric power will be a total of one dollar per mole of product. In the foreseeable future when producing isotopes in small amounts the cost of capital investments in lasers and the cost of the manpower will undoubtedly be higher than the cost of the intake power. Nevertheless the possibility of a significant reduction in production cost of stable isotopes by the laser methods is entirely obvious.

## 7.3. Laser Production of Pure Materials

Methods of selective effect of laser radiation on matter developed for laser separation of isotopes go from the theoretical and practical point of view beyond the frame of this specific problem. In essence, we are talking about a new approach to the technology of obtaining materials on the atomic-molecular level when with the help of laser radiation it is possible to manipulate the atoms and molecules of defined type directly, that is, collect the macroscopic amounts "one atom, one molecule." As one such broad application of powerful laser emission, let us consider the laser production of especially pure materials. For selective deep purification of a material by laser radiation it is possible to use the processes of selective ionization of the impurity atoms and selective dissociation of the impurity molecules.

The method of selective ionization of the atoms appears very attractive, for it has high universality and flexibility. The optimally selected system of selective step photoionization of an atom under the effect of two (or more) laser beams with frequencies tuned in a defined way will permit ionization of each atom for a time on the order of $\tau = 10^{-5}$ to $10^{-7}$ sec with a radiation intensity at each frequency on the order of 10 to $10^2$ watts/cm$^2$. For total use of the radiation energy for photoionization of the atoms with ionization energy of $E_i$ = 7 to 8 ev and transverse cross section of the light beams of 1 cm$^2$, this power corresponds to the ionization of approximately 1/2 mole of material per hour. Consequently, the establishment of the laboratory scale can theoretically provide for the release of about 1 ton of material per year. Therefore the method of selective ionization of atoms combined with tunable dye lasers with an output power of 10 to 100 watts can be considered as a sufficiently productive method of fine separation of materials on the atomic level.

Laser purification of matter by the method of selective ionization with respect to the operating principle does not differ from the separation of isotopes, but it requires higher separation factor, for example, more than $10^3$. This method potentially has a number of significant advantages by comparison with the existing methods of purification of materials based on the difference of certain chemical or physical properties of the purified matter and impurities.

First, the laser method can theoretically have extraordinarily high selectivity. The degree of purification of matter in the process of separation of the given element from any admixture can reach values of more than $10^3$. In particular, if for purification we take a mass produced material with purity of $10^{-7}$%, then by the method of selective ionization of the atoms it is possible to realize purification to $10^{-10}$%.

Secondly, this method is highly universal. Selective ionization can be realized by selecting the frequencies of tunable lasers in practice for any element independently of its physical and chemical properties (melting and boiling points, reactivity, and so on). If it is necessary to purify the

material of one or several previously defined elements, then selective ionization of the impurities alone and removal of them from the atomic beam of the evaporated material are possible. In this mode it is possible to achieve maximum output capacity and minimum expenditures of light energy. Thirdly, the method appears to be highly flexible for direct production of a material in the form of films, including with complex stoichiometric composition. The ion beam can be directed to the surface of the substrate in order to obtain a pure film of the given element. The entire process of selective ionization of atoms, the extraction of ions from the beam and deposition of them on the substrate can be realized in a deep vacuum. The basis for the successful development of this method is the development of lasers in the visible and ultraviolet ranges with tunable and controllable frequencies, with high average power and long service life. Average powers of 1 to 10 watts are needed for laboratory experiments, and $10^2$ to $10^3$ watts for experimental industrial devices.

The method of selective dissociation of molecules can be successfully used for the purification of matter in the gas phase to remove molecular impurities, the elimination of which by orinary methods is inefficient. The purification by the dissociation method is based on the difference of the physical-chemical properties of the basic material and the products of dissociation. This makes it possible to use ordinary methods for purification at the end of the process after irradiation of the mixture. The possibility of deep purification of a gas mixture to remove molecular impurities by selective multiphoton dissociation of them by strong infrared radiation, was demonstrated in 1976 in the joint experiments of the Spectroscopy Institute of the USSR Academy of Sciences and the Scientific Research Institute of Material Sciences of the MEP. In these experiments one of the important materials of semiconductor technology, arsenic trichloride $AsCl_3$ was purified of basic impurities: 1,2-dichloroethane $C_2H_4Cl_2$ and carbon tetrachloride $CCl_4$. The usual methods of purification give the maximum content of the given impurities no less than $10^{-2}$ to $10^{-3}$%. The absorption bands of $C_2H_4Cl_2$ and $CCl_4$ fall in the region of generation of the $CO_2$-laser, and therefore they dissociate quite effectively when tuning the generation frequency to their absorption bands. In the case of 1,2-chloroethane, the products formed differs sharply with respect to their physical properties from arsenic trichloride, which permits easy separation of them and insurance of purity of the $AsCl_3$.

An important product of semiconductor technology -- $SiH_4$ gas -- also can be purified of all molecular impurities which usually absorb radiation in the vacuum ultraviolet, for example, in the range of 1900 to 2000 Å at the same time as the $SiH_4$ molecule absorbed only shorter wave radiation, and therefore it does not dissociate. This experiment was often successfully realized in the laboratory of applied laser photochemistry in Los Alamos (US) and has now been introduced into technology for obtaining especially pure silicon.

The method of selected dissociation is also applicable for purification of gas mixtures to remove toxic and cancerogenic materials.

## 8. THERMAL EFFECT OF LASER RADIATION

### 8.1. Processing of Materials

The high power of a laser beam is sufficient for the melting and evaporation of any material. In combination with short heating time, small size of the local heating zone, independence of heating with respect to the mechanical properties of the material, simplicity of control and transportation of the light energy this opens up broad possibilities for the application of powerful lasers for working both metallic and nonmetallic materials.

Let us note that the principles of the technological applications of laser emission were developed in 1965-1970. Then it was demonstrated that it was prospective to use the radiation of various lasers themselves -- solid-state and gas -- for welding, cutting and thermal hardening of materials. It turned out that in order to perform many of the technological operations relatively small power levels are sufficient -- on the order of 10 to 200 watts. At the present time hundreds of samples of laser technological equipment has been prepared both in our country and abroad whic are being successfully used in industry. For example, at the ZIL plant for laser heat hardening Soviet Industrial Kvant-16 laser units [illegible] using a solid state laser are applied. Let us emphasize that there is a broad range of technological applications of laser emission for which neither high power nor high pulse energy of laser emission is required. Standard examples are as follows: the electronic industry (precise contactless fitting of the microcircuit elements, and so on), precision machine building (exact contactless balancing of pendulums, gyroscopes, and so on), the watch and clock industry, and so on. The economic and technical effectiveness of such laser applications, in spite of the comparatively short period of their development, have already been firmly proven.

However, this entire class of problems is beyond the scope of our booklet. We should like to limit ourselves only to the problem of the application of powerful and superpowerful laser radiation generated on unique devices.

Among the numerous family of high-power lasers for welding, cutting and hardening materials, the greatest attention is given to the continuous $CO_2$-lasers investigated in Chapter 3. It is this type of laser that with respect to an entire series of theoretical and technical characteristics now

finds the greatest application in industry for the processing of materials. The experiments show that in order to machine (drill, cut, weld) one mm of metal approximately 1 kilowatt of power of continuous laser emission is required. Therefore the power of the lasers required for various types of machining of thick materials is within the range from 1 kilowatt to several tens of kilowatts.

Successful experiments with respect to the machining of materials by continuous powerful laser emission are being conducted in the USSR under the direction of academician Ye. P. Velikhov (in the laser machining laboratory of the VIL jointly with Moscow State University imeni V. M. Lomonosov and the Nuclear Power Institute imeni I. V. Kurchatov) and the United States (the "Avco" and "United Technology" Companies). On the created experimental technological units with continuous $CO_2$-laser, the prospectiveness of the use of powerful laser emission for cutting, welding and local heat hardening (quenching) of metals and alloys was demonstrated. Of course, the application of quite expensive laser emission is economically expedient only in cases where the existing methods turn out to be ineffective.

Laser welding is expedient in cases where advantages are obtained which arise from the localness of the laser heating by a powerful laser beam with small divergence: small shrinkage of the material, small deformations during welding, the possibility of deep fusion with a high welding rate. Figure 27 shows the welding thickness as a function of the power of the laser emission obtained in the mentioned joint ZIL-MGU [Moscow State University]-IAE [Nuclear Power Institute] experiments. For comparison in Table 3 we have the arc and laser welding parameters of steel 20 mm thick calculated per running meter. The advantages of laser welding can also include the possibility of welding several welds simultaneously, carring out welding and heat treatment, machining with large distances of the source from the part in places that are difficult of access, easy regulation of intensity, and so on. However, in spite of all these advantages, laser welding is still in the state of experimental operation. It is necessary to solve a number of problems (high requirements on the accuracy of placement of the welded joints, reliable optical system for shaping and guiding the powerful laser beam, and so on) before it will be possible to realize the advantages of laser welding in series production practice.

Laser cutting can be realized either by evaporation of material or by fusion with blowing of the melt out of the cutting zone by an inert gas. Gas laser cutting using oxygen is also possible where the laser heats the material to the combustion temperature. For laser cutting it appears possible to carry out complex and precise shaped pattern layout both with respect to the outside surface of the part or sheet and with respect to the inside surface. For a layout of nonmetallic materials, the use of laser radiation gives record machining speeds with good quality of edges. For example, polyester plastic with glass filler (material for the panels of a truck body) 33 mm thick in joint ZIL-MGU-IAE experiments was cut by a 0.4 kilowatt laser with a speed of 1.5 m/min. At the Ford plants in the United States a laser is used to work silicon nitride -- a hard ceramic material used for gas turbine

Table 3. Comparison of arc and laser welding per running meter of steel 20 mm thick (according to the data of the ZIL-MGU_IZE experiments)

| Parameters | Arc welding | Laser welding |
|---|---|---|
| Speed, m/hr | 10-15 | 50-150 |
| Number of passes | 5-8 | 1 |
| Welding time, minutes | 32 | 0.6 |
| Power input, kilowatt/hr | 2.5 | 0.6 |
| Weld width, mm | 20 | 5 |
| Electric power intake, kilowatt/hr | 6 | 2.5 |

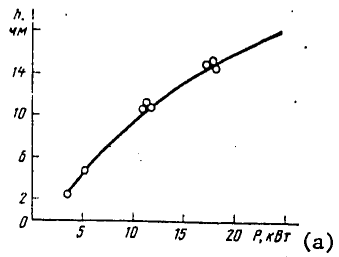


Figure 27. Weld thickness h as a function of the power of the focused beam of a continuous $CO_2$-laser with welding speed $v_{weld}$ = 144 cm/min obtained at the branch of the Nuclear Power Institute imeni I. V. Kurchatov, Moscow State University and ZIL Institute.

Key a. kilowatts

engines. The laser beam cuts this material 10 times faster than a diamond tool.

High cutting speeds, small width of cut, absence of wear of the tool, independence of the thermal characteristics of the material and its hardness, the possibility of automation of the process -- all of these advantageously distinguish the laser cutting from other methods, and in individual cases makes it simply irreplaceable. At the present time a 10 kilowatt $CO_2$-laser with blowing the cutting zone with oxygen can be used to achieve cutting of different steel parts up to 20-40 mm thick, nickel alloys to 10 mm, tantalum and niobium to 5-10 mm, and so on.

Although the basic method of finishing the metal in all branches of the metal working industry and automobile-building is gas flame cutting, laser cutting is being studied intensely and is being developed in the USSR, the United States, the Federal Republic of Germany, England, Sweden, the German

Democratic Republic and other countries. Laser cutting is most expedient and effective for nonferrous metals, alloys with special properties, for laying out compositional materials and also steels and other metals coated with protective means and where a small weld-affected zone and narrow cut (about 1 mm) are required.

One of the most interesting and promising applications of powerful laser emission is surface heat treatment of material, quenching or hardening. The advantage of laser quenching consists in the possibility of localization, that is, machining of the section most subject to wear. This reduces the required amount of heat fed to the part to a minimum and at the same time decreases its deformations and undesirable structural changes. Another advantage is that laser emission can be used to machine holes or complex configurations inaccessible for thermal and induction quenching. According to the estimates of the specialists of the General Motors Company (United States) at the plants of which laser quenching of responsible automobile parts has already been put into mass production, the application of laser emission has made it possible to reduce the expenditures on heat treatment by 80%. This is achieved as a result of eliminating deformations of the parts and excluding at the same time the necessity for machining the parts after heat treatment. The localization of the heat treatment greatly reduces the power expenditures also.

The scientists of the Nuclear Power Institute imeni I. V. Kurchatov, Moscow State University imeni M. V. Lomonosov jointly with the specialists of ZIL have investigated the laser thermal hardening of different types of cast iron and steel used in the automobile industry, with the help of a $CO_2$-laser of up to 5 kilowatt power. The hardness of the cast iron and the steel after laser quenching has increased on the average by 3-5 times. This opens up the prospects for further development of the method of laser quenching for introduction of it into mass production.

At the present time as comparatively simple and available continuous $CO_2$-lasers are developed with a power of tens of kilowatts, studies have begun to determine the possibilities of working materials which appear to be science fiction projects until recently. As an example it is possible to present the study of the interesting and prospective possibility of crushing and cutting rock by powerful laser emission. The experiments presented using the powerful $CO_2$-laser at the Nuclear Power Institute imeni I. V. Kurchatov demonstrated that the energy consumption of crushing rock samples made of quartzite, albinite, granite, diorite and marble is within the range from 0.1 to 1 kilowatt per $cm^3$ of rock. The creation of superpowerful continuous lasers obviously makes high-speed tunneling through solid rock with powerful laser emission realistic.

8.2. Laser Jet Thrust

Under the effect of quite intense laser emission on a target, heating of the target takes place, evaporation and ejection of vapor from the surface. This creates a jet pulse, to the existence of which the Soviet scientist G. A. Askar'yan gave his attention already in 1962 in the first experiments

with a ruby laser. After the development of powerful continuous lasers this mechanism of creating the jet thrust was used in designing a laser jet engine (LRD) which was proposed by one of the directors of the Avco Everett Research Laboratories, doctor A. Kantrovits. The idea for this proposal is very simple. A high-power laser beam is continuously fed to the surface of the solid working medium of the rocket from a ground-based laser energy source. The heating and evaporation of the working medium by the laser emission provide the jet thrust. Here, just as in the usual jet engine, when the rocket moves it loses mass with evaporation, but not as a result of combustion, that is, a chemical source of energy, and as a result of the high-temperature heating of an incombustible material. Theoretically it is possible to use this method to achieve acceleration of a flight vehicle at a distance of tens of kilometers with the help of a laser jet thrust, that is, insert a flight vehicle into artificial earth satellite orbit.

Of course, there is a serious problem of transporting a powerful laser beam from a ground based laser to the surface of the rocket to the distance of actual flight. For example, in order to transport the laser beam a distance of 100 km (low artificial earth satellite orbit) with a nozzle-target diameter of 1 meter it is necessary to insure divergence of the laser beam of no worse than $10^{-5}$ radians, that is 2 angular seconds. This presents serious difficulties in the real atmosphere which has natural nonuniformities and also inhomogeneities induced by the powerful laser beam. Simple estimates show that in order to insert a vehicle into artificial earth satellite orbit with a finite mass of 100 kg it is necessary to evaporate 300 kg of graphite by a laser beam with a power of about $10^9$ watts over the course of about 10 seconds. The creation of a laser device with such power would provide for the insertion of light artificial earth satellites into orbit using a stationary power source located on the earth. It is true that the possibility of creating such a "superlaser" with 1 gigawatt of power appears to be highly problematical.

Recently corresponding member of the USSR Academy of Sciences F. V. Bunkin and academician A. M. Prokhorov investigated the possibility of creating a laser air-jet engine (LVRD). The idea of this engine constists in heating atmospheric air in the rocket with powerful radiation coming from the ground or one other flight vehicle. In this case the only working material of the engine would be atmospheric air, and the mass of the rocket inflight would be constant. It is true that such an engine can insure acceleration of a rocket only within the earth's atmosphere. For realization of the LVRD it is necessary that the radiation intensity in the heating air be quite high and the heated air must have sufficient absorption of the laser emission. At the same time in the laser beam itself propagated from the laser to the rocket, the intensity must be below the nonlinear absorption threshold. Therefore the LVRD must have a system for focusing the received laser beam to increase its intensity. The required absorption coefficient of the laser emission inside the heating region can be realized as a result of the occurrence and the self-support of the optical discharge in the air during laser irradiation.

The most advantageous is the pulsating (pulse-periodic) operating mode. Each radiation pulse should pass through the atmosphere without significant absorption and hit the parabolic reflecting surface which is in the tail section of the rocket and rigidly connected to it. In the focal region intensities are reached which exceed the optical breakdown threshold of the air itself which is located there. The optical breakdown or explosion in the focal region excites a shock wave in the cold air surrounding it which on propagation acts on the reflecting surface, simultaneously servicing as a pressure receiver. On arrival of the next laser pulse the focal region must be filled with cold air, and the process can be repeated periodically. As a result of the pulse-periodic irradiation, a train of shock waves occurs which gives the jet thrust. The potential advantage of the LVRD over the LRD is the fact that the working medium is only atmospheric air, and therefore the final mass of the flight vehicle coincides with the launch mass. The requirements on the average power of laser emission for the LVRD are approximately the same as for the LRD with the evaporative mechanism of thrust.

The idea of using a laser energy source placed outside the flight vehicle to create a jet thrust is still on the level of scientific research. Now it is still not clear whether in the future it will lead to the creation of real LRD. The success depends primarily on progress in the building of lasers with extraordinarily high average power exceeding hundreds of megawatts.

## 9. LASER BEAMS AT LONG DISTANCES

In the optical range of electromagnetic waves it is entirely possible to make the transverse dimensions of antennas (telescope, mirror) millions of times longer than the radiation wavelength. Therefore the spatially coherent light field can be formed as a beam collimated to the highest degree, the divergence of which in accordance with (1.1) is equal to the ratio of the wavelength to the transverse diameter of the beam. Hence, numerous potential applications follow naturally: the laser location of artificial earth satellites in the moon, long-range space communications, transportation of light energy to cosmic distances. Many of them have been demonstrated the first years after building lasers.

The optimism of these early works and proposals was also noted in the specialized and popular science literature. In reality the problem of creating and controlling highly collimated light beams with high power is a highly complex scientific-technical problem which in practice has not been solved on the required level in powerful lasers of the first decade. Therefore the results obtained during the first ten years, in spite of their importance still do not reflect the entire scale of the problem. Obviously, only further progress of powerful lasers, methods of control and correction of the wave fronts of the highly collimated light beams by the means of adaptive optics will actually lead to the realization of colossal potential capability of the collimated powerful light beams in technical complexes. Here we shall consider very briefly only some of the possibilities in this field.

### 9.1. Laser Location of the Moon

The idea of optical location of the Moon was realized in the United States and the USSR soon after the building of lasers. The accuracy of measuring the distance to the moon in these experiments was determined by the duration of the laser pulse ($10^{-3}$ seconds), that is, it was about 150 km. However, in 1965 equipment was built at the laboratory of academician N. G. Basov at the Physics Institute imeni P. N. Lebedev suitable for one-time measurements of the propagation time of light or distances to the moon with an error not exceeding $10^{-7}$ sec, that is, $\pm$15 meters. For the first time this equipment was used to measure distances to the moon with satisfactory accuracy at that

time (~200 meters). The error was determined by the nonuniformities of the lunar relief within the boundaries of the light spot and not by the equipment.

Beginning in 1967, all of the work with respect to laser location on the Moon was connected with planning the launch of the Lunokhod spacecraft to the Moon in the USSR and the Apollo spacecraft in the United States with corner light reflectors on board. During the 1969-1973 period, Soviet and American vehicles delivered five light reflectors to the Moon. The use of these light reflectors and lasers with short radiation pulses made it possible to proceed with experiments with time resolution of $\Delta\tau = 10^{-8}$ seconds. Now laser Moon locators have been built with time resolution of $\Delta\tau = 10^{-9}$ sec, and locators are being designed with $\Delta\tau = 10^{-10}$ sec. Special time interval meters have been developed for them which were constructed by the analogy or nonius principle which have the indicated time resolution. The accuracy of measuring the distance to the Moon by laser locators is now limited by the accuracy of consideration and exclusion of the atmospheric corrections which is possible only with an accuracy to 2-3 cm (!). It is true that the energy characteristics of the modern laser lunar locators are quite moderate. The reception of the reflector signal (the emitted energy is usually several joules) insures the appearance in the receiving channel of on the average from hundredths to tenths of a photoelectron calculated per laser pulse. Therefore the signal is recorded by statistical accumulation and requires complex electronic equipment. With this low level of useful signals the success of the measurements depends strongly on the meteorological and astronomical conditions.

Now an entire network of stations has been built and is continuing to be developed for laser location of the Moon. The presence of several fixed light reflectors on the Moon and several stations spaced far apart on the earth permits measurements to be made which are of interest for many scientific problems of the earth-moon system: investigation of the movement of the earth's holes (the expected accuracy of about 30 km, which is an order more accurate than the existing methods of measurement), more precise determination of the laws of rotation of the earth (measurement of the relative longitudes with accuracy to 0.01 angular seconds), study of the drift of continents, more exact determination of the orbit and laws of orbital motion of the Moon, investigation of the rotation and study of the configuration of the Moon. For many of these problems, the creation of mobile laser-location stations capable of performing measurements with high (2 to 3 cm) accuracy and having energy efficiency sufficient for lunar location is especially prospective.

9.2. Long-Distance Space Communications

As spacecraft penetrate into deep space within and beyond the limits of the solar system obviously the potential capabilities of high-power, highly directional laser beams for communication with them will play an increasing role. Even relatively simple incoherent communications systems using short nanosecond pulse lasers with high repetition frequency (tens of megahertz)

on board the spacecraft and ground multireflector light collectors with a diameter of 10-20 meters with direct incoherent light detection can insure very high speed data transmission ($10^5$ to $10^7$ bits/sec) from distant space, for example, from the Neptune orbit. These parameters are unattainable by any other means with reasonable requirements on the size of the spacecraft, the mass and cost of the communications system. The high capacity of laser communications systems will permit images to be received in real time and the use of video information for operative control of the spacecraft from the ground.

With limited power of any communications system with targets located beyond the solar system obviously the only reasonable possibility is the use of a laser communication system. Of course, the difficulties of realizing communications at interstellar distances are very great. However, as one of the creators of quantum electronics, American scientist professor C. Towns noted immediately after discovering lasers, such properties of powerful laser emission and acute directionalness of the coherent light beam, high pulse power which greatly exceeds the noise contribution of the background emission of any star make interstellar communications entirely realizable. Of course, for the reception of a signal enormous multireflector light collectors are required either on the ground or in artificial earth satellite orbit. Simple estimates indicate that a laser pulse with an energy of $10^4$ joules lasting 1 nanosecond with divergence of $10^{-6}$ radians = 0.2 angular seconds can be recorded on the ground from a distance of 1000 light years with reception of the signal by an optical reflector 100 meters in diameter.

Long distance communications at cosmic distances is one of the great prospecitve areas of tomorrow which will stimulate the development of powerful laser systems as the demand for this form of communications increases. Even the rapid development of science and engineering in our time still has not brought to realization many of the colossal potential capabilities of coherent light, including the possibility of creating laser long-distance space communication systems.

9.3 Transportation of Light Energy over Great Distances

The mastery of outer space and, in particular, the creation of long-term space laboratories are opening up a new field of activity for quantum electronics which goes beyond the scope of the transmission of optical signals to cosmic distances and cosmic locations and adjacent to the problems of power engineering. On the one hand, we have constantly active and free source of incoherent light energy from the Sun in outer space. In near-earth orbit a collector with a diameter of 300 meters collects approximately 100 megawatts of light energy. The cost of this energy is determined only by the cost of building and maintaining a light collector in orbit. On the other hand, large space stations are in need of powerful power supplies. At the present time this problem is solved by using solar batteries directly converting sunlight to electricity. The principles of quantum electronics permit another path to be seen for the use of solar energy and transmission of it great distances on scales greatly exceeding the present demands of

space stations. This path consists primarily in the creation of orbital lasers pumped directly by sunlight, secondly, the transmission of light energy in the form of highly directional coherent light beams both to space stations in need of power and to the Moon, the Earth and so on, and thirdly, the direct conversion of the energy of the laser emission to convenient electric power for the majority of applications. Today probably we are in the initial phase of developing all of the required key components of the future laser-solar power engineering.

The creation of large orbital high-power lasers pumped with sunlight is now being investigated as an entirely realizable program. The first laser with solar pumping was built in 1963. As the amplifying medium it used $CaF_2:Dy^+_2$ crystal cooled to a temperature of 27° K. Now for operation in outer space studies are being made of much lighter, more available, cheaper and more effective amplifying media. Probably these will be gas media pumped by radiation which will be gathered by using a light collector with a diameter of several hundreds of meters. Solar power insures a power density of 1350 watts/$m^2$ of the collector with effective temperature of about 6000° K (it is true, with a shortage of ultraviolet radiation). Of course, far from this entire broad spectrum is used for pumping, and therefore probably the sunlight collector will be a type of filter which reflects only the spectral interval required to pump the laser. The transverse dimension of the laser will probably be several meters, and, as usually occurs in powerful lasers, its divergence will be far from ideal. For transporting laser energy to cosmic distances, the so-called adaptive reflector will be used with a diameter of several tens of meters which will compensate for the nonuniformities of the wave front of the laser beam, converting it to the maximum directional light beam with diffraction divergence of $10^{-5}$ to $10^{6}$ radians. Such a light beam will be able to be transported distances of thousands of kilometers with insignificant increase in its diameter.

Another key element is the converter of the energy of a laser beam directly to electricity. Of course, for the conversion of laser beams in the visible and ultraviolet bands it is possible to use devices such as solar cells. However, it is more probable that superpowerful orbital lasers will operate in the infrared band on oscillatory transitions of molecules. In this case the thermoelectric converters will be more suitable. Recently at the NASA Laboratory in the United States such a converter was successfully tested which was developed as an element for the transmission of energy from ground lasers to satellites. The thermoelectric radiation converter of a 10 kilowatt $CO_2$-laser is based on the absorption of a laser beam in a plasma and heating it to high electron temperatures. The high-energy electrons diffuse from the plasma and block the electrodes in the plasma element, causing the appearance of a current in the external circuit. The estimates show that the efficiency of this converter of infrared radiation can reach 40%. The performed experiments indicate the possibility of creating a power converter for laser infrared radiation of up to several megawatts.

In the first phase of creation of the laser-solar power systems in space it is planned to lower the mass of the power plants of the satellites from

75% of the total mass of the satellite (today) to 25% (in the future) when supplying laser radiation first from the ground lasers and then from orbital lasers. In the next phase it will be possible to transmit light energy to large stations on the moon and, finally, to the earth to increase the power engineering potential. This path of the use of solar energy appears to be entirely logical in the chain of scientific-technical achievements and current requirements of mankind. It appears entirely probable that in the future it will be advantageous to create large laser electric power plants at distances closer to the Sun than to the earth. For example, in Mercury orbit the density of the solar energy is about 10 kilowatts/$m^2$ and, consequently, the specific power pickup is increased by an order, and the set of potentially possible amplifying media is expanded. Of course, this type of plan for laser solar power engineering is beyond the limits of the technical possibilities of the 20th century.

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